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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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THE GEOLOGIST IN PUBLIC WORKS

BY CHARLES P. BERKEY

(Address as Retiring President of the Geological Society of America)

It has become a custom in this Society, fixed by formal observances of more than half a century and by the example of a long line of elders, to the number now of more than fifty, for the President of the year to deliver an address closing his administration. As to content or method of treatment there seems to have been no rule. A review of the titles indicates that the larger number have chosen topics representing their major lifetime interests. Only a few are philosophical, although there are many such observations tucked away in others. An occasional one has the evident purpose of bringing an important current problem or policy into the limelight, while more rarely a forward look either for the good of the organization or for the advancement of the science may be discerned.

Only three are missing—that of James D. Dana in 1890, that of Alexander Winchell in 1891, and that of G. K. Gilbert in 1909. Three are mainly historical, one is concerned with branch relations, seven are philosophical in general character, six have to do with major elements in geologic problems, two are regional studies, four are devoted to Pleistocene Geology, four are on mineral resources and economic relations, two on the pre-Cambrian, two on applied geology, and fourteen on specialistic research and individual interest.

The individual addresses [1] constitute a strikingly comprehensive lot that would bear reprinting in full in a separate volume. In them in each instance are valuable experiences and bits of wisdom from the famous men who wrote them. Evidently there is no limit to choice of subject. A president may present whatever seems to him to be suitable to the occasion, and as far as I can discover there is no way of changing his decision.

In my own case there has been more uncertainty than usual, for it seemed that there might be fair excuse for considering several possibilities. I might have elected to talk on the *Nature of the contribution of petrology to geologic history*, for that field has been a major interest for

[1] These addresses are largely lost in the large volume of the Society's publications now in their fifty-third year. The complete list is given at the end of this paper.

longer time than any other,—dating back to the early teaching days in Minnesota and the discovery of Professor Grout. It would have been appropriate also to assemble a *Summary of the geological explorations in Central Asia,* since those studies, begun in better days than these, still continue.

In view of the fact that more than 50 years have been spent in teaching one might claim the privilege of discussing *Trends in geological education.* But I am reminded that Professor Shaler, just 40 years ago, upon retiring from the presidency, addressed the Society in this city on that topic, and, considering his fame in that field, I have no comment to offer.

As a matter of fact the choice of a topic was not left to such incidental considerations. The subject was really fixed by experiences that left no practical alternative. For it has been my fortune to inherit a major interest from the traditions of my elders, chiefly the two famous men who preceded me in Columbia—Professor John S. Newberry and Professor James F. Kemp—and Professor W. O. Crosby of Massachusetts Institute of Technology, all of whom had keen interest and close contact with Applied Science and its problems and who won special recognition in advisory service on the public works of their day. Long before my own special interest was aroused it was my often-repeated privilege to accompany such men on their field investigations and make laboratory tests and identifications for them. So it happened that in the normal course of events more and more of their responsibilities fell on my shoulders. Soon practical questions began to come to my own desk. It is not necessary to assume that they came by reason of any outstanding personal reputation or special promise. But the fact remains that they did come and have continued to come with more exacting responsibility from that day to this.

That work first brought independent responsibility in the summer of 1906 when both of the regular geological advisers of the Board of Water Supply of the City of New York, Professors Kemp and Crosby, were not available. In that emergency J. Waldo Smith, the chief engineer of the project, sent me to Browns Station in the east foothills of the Catskills on a characteristic mission. He simply wanted to know whether anything could be made out of a lot of exploratory data by that time gathered from borings, test pits, and trenches designed to expose the physical condition of the four possible sites for a dam and reservoir, which was to become the head of an entirely new supply of water for the City of New York. When that commission was shortly finished with the assurance that one of the four dam sites was distinctly superior in its geological setting, a second task was set—that of finding a place for the aqueduct

then planned to cross the Hudson River Valley and gorge. It was especially desired to avoid if possible the expected dangers of a great regional fault that almost everyone assumed lay beneath the river gorge. That was a severe test of the possible helpfulness of geology on one of the key problems affecting the plan and design for this, the most complex project attempted up to that time in this country. By and by, however, that study also was completed, and then it was fully expected that such geological service would soon end. On the contrary the larger part of a long lifetime has since been crowded with like practical questions raised in connection with this project and others of similar character. In that manner a veritable flood of practical problems has come, which have developed into a field of large public service.

As commonly happens on such extra work, odd hours and nights intended for rest were sacrificed to this purpose. Weekends normally intended for recreation were devoted instead to the exacting drudgery that characterizes such service. Sundays often became like other days, and for many years there were no summer vacations to relieve the strain of never-ending effort in what was then considered a great opportunity. For those early days on the Board of Water Supply were almost the beginnings of the recognition of the geologist in the construction of great engineering works in the United States. Up to that time such geology as was practised was chiefly that of the engineer himself supported only with an occasional call upon a geologist for a special study or an opinion on some unexpected trouble.

To my best belief this was the first time in the history of the science in America that a geologist was given free rein from the very beginning to make such studies as he thought advisable and to stay with the project to the end. In this instance he was given the privilege of originating suggestions and was allowed to follow them up to determine whether the service had been worth while. In that way the case was finally proven for Engineering Geology. A greater variety of problems connected with the ground had been given adequate study than in any other project to that time.

The original Catskill Aqueduct alone included about 50 miles of cut-and-cover construction, 35 miles of pressure tunnels, 15 miles of grade tunnels, and 5 dams and reservoirs. These works penetrate or otherwise depend upon 37 different geologic formations; cross 6 sizeable rivers with tunnels under pressure, including the one under the Hudson gorge at Storm King, a short distance above West Point, at 1100 feet below sea level; and 3 mountain ranges where grade tunnels could be used. These works cover virtually the whole range of rock structure and phys-

ical condition known from the pre-Cambrian through more than half the geologic column and reach from the Catskill Mountains to the coastal margin of Staten Island.

Literally thousands of minor questions were raised by the very complex situation exhibited in these works. The number of mistakes and costly blunders chargeable to unexpected troubles and from undiscovered physical conditions was insignificant. Instead of the flood of claims that sometimes amounted in other projects to more than the original estimates, these contracts held reasonably true, and there was not a single scandal to spoil the reputation of this great undertaking. More than 30 years have gone by, and the Catskill Aqueduct is still in perfect running order.

Now, 30 years later, as already noted, the works for a second great supply, including the Delaware Aqueduct, are building. Nearly 100 miles of deep tunnel, from 500 to 2000 feet in depth, have already been excavated. Two dams for storage reservoirs are under construction, and within reasonable time, with their addition, the City of New York can be assured of more than a thousand million gallons of water per day from the Catskill region alone.

It was my good fortune to have come to the City of New York at a very opportune time. All its facilities were outgrown, and the golden age of its engineering expansion had just begun. In that very year the unique department known as the New York City Board of Water Supply was created. That Board alone has constructed works exceeding 500 million dollars in developing water supply for the citizens of New York. In its planning and construction there was a great field for the professional engineer and a unique opportunity for a practical-minded geologist. It is believed that it is a more perfect system because of the aid that geology has given than it would otherwise be. This work among many other contributions from other interests is back of the reputation of the several projects of the City of New York. This picture lies in the background behind the subject of the evening—this and scores of other works of similar character and significance. But since that time municipal, industrial, and federal projects of similar character to the number of more than 100, widely distributed over the United States, have been studied by the writer in like manner. Thus through a wholly unexpected combination of circumstances, such, perhaps, as could never happen again, this kind of geological service came into great prominence and for a quarter of a century has enjoyed marked favor and responsibility.

A list of projects that have been studied personally would be too long for inclusion here, but it is practicable at least to make appreciative

mention of certain administrative bodies that have used geological service extensively in connection with their public works.

In this field the Board of Water Supply of the City of New York, because of its long record, because of the complexity of its problems involving geological investigation, and also because of its vital importance to a large metropolitan population, probably stands in first rank. Similar works and like methods of building them have been pursued by many other organizations, among them the Metropolitan District Water Supply Commission of the Commonwealth of Massachusetts, the Department of Water and Power of the City of Los Angeles, and other cities on a somewhat smaller scale.

Certain other large interests, especially Federal agencies, centered on flood control and improvement of navigation, water conservation and irrigation of arid lands, and the production of power, have followed the same lead in building their dams and reservoirs, their locks and bridges, railway and vehicular tunnels, highways and subways, and all manner of works connected with such development. The largest program of construction for such purposes is that of the United States Bureau of Reclamation with engineer headquarters in the city of Denver. No less than 50 dams and reservoirs have been lately constructed or are now building. Another, which is unique in that a whole river with its tributaries is under systematic development, is the government agency known as The Tennessee Valley Authority with headquarters at Knoxville, Tennessee. Since 1933 when Norris dam was begun this engineering body has built 12 similar structures and has 8 others under construction —all engaged in the production of power and providing river regulation and improved navigation facilities.

The largest undertakings such as those mentioned above are themselves complex both in character and purpose as well as in the physical conditions they have to meet. A large structure such as Boulder Dam serves several purposes, the chief one being the production of power. But it also accomplishes water conservation, flood control, and river regulation, with irrigation and power as the chief end products. Incidentally it has become a sort of mecca for the American tourist who has come to regard it as the most striking exhibit of the many works of the conservation engineer of The Far West. That great structure was sponsored and planned by the United States Bureau of Reclamation, an active construction agency and the most consistent present user of engineering geology in public works. That Bureau has been responsible for a great number of such works in the last 20 years, amounting by this time to fabulous sums for construction. A representative list would include such

great works as the Grand Coulee Dam on the Columbia River, the Owyhee and Wickiup in Oregon, Marshall Ford in Texas, Caballo in New Mexico, Parker Dam between Arizona and Nevada, Bartlett Dam in Arizona, Friant and Shasta dams in the Central Valley of California, Deer Creek and Moon Lake in Utah, Alcova and Seminoe in Wyoming, Island Park and Anderson Ranch in Idaho, Green Mountain, Taylor Park and Vallecito in Colorado, and many others of like caliber.

Despite the reputation of geologic service in recent years actual expansion of its use came slowly. But when the St. Francis Dam of the Los Angeles water system, shortly after completion, was undermined and collapsed on its own weakened foundations, carrying in its flood waters death and destruction to a whole valley, a new realization of its vital character came swiftly. That happening of 1927 is an old story now. It is not easy at this distance to picture the dismay that this failure brought to the engineering profession. Although there were many different reasons suggested, every board of investigation in that instance held that the geological conditions had not been met and that this was the chief cause of failure. Ultimately that explanation was accepted at full value, and since that time no great structure of that kind has been attempted without more or less competent advisory confirmation or specialistic geological advice.

But the most striking change was in the make-up of the Advisory Commissions and Boards of Consultants on great public works of that class. Up to that time, in the average case, if a geologist had anything at all to do with a project he was simply called in for occasional conference or to give his opinion as to new work or to determine the reason why the plans had failed. From the time of the St. Francis Dam failure, however, the geologist had a place; he became a co-ordinate member of the Board itself and was given opportunity to make his own studies and express his own views in time to reach the design table and the testing laboratory and the construction conference and the drafters of the contract.

Appointment of the Colorado River Board in 1928 by President Coolidge at the direction of Congress was the first formal recognition of the changed situation. A famous engineer of the War Department, General Sibert, builder of the Gatun Locks, was named Chairman of a Board which was filled out with two engineers and two geologists who were directed to settle a controversial question as to the feasibility of the Boulder Project that had agitated Congress for several years without material progress. Finally they came to the very practical decision to find through a board of experienced specialists whether or not a Boulder

Canyon dam could be built. The recommendations of this Board were so definite and understandable that the project was promptly authorized. Everyone realized the enormously difficult geological conditions as well as the greatness of the engineering undertaking. It was a joint task of extreme difficulty and many problems, and the fact that the great dam and appurtenant works were successfully constructed gave great impetus to like co-operation of engineer and geologist in other undertakings. Since that time no great public work of that type has been undertaken without provision for geology from the very beginning. Generally one or more practical geologists are attached to the Advisory Board with additional full-time staff appointments to keep constant touch with development of the physical situation.

It is easy to see from this long explanation that there is nothing very obscure about the topic I bring before you. To be sure, it lies far out on the borderland where in former time it was completely overshadowed by other more spectacular features. From that situation it has been rescued by the emergencies of our strange time, especially the demand for power. With that demand we geologists have developed a service of our own that has won considerable credit from those who construct great public works.

At this point I might end my dissertation, for everyone is more or less aware of the importance of these great structures. I might do that except for the new interest thrust upon these works. A large portion of the power that is expected to save our civilization is now coming from these sources. Except for some of these works the effort that the United States in its "all out" is now putting forth would be impossible. Perhaps the salvation of the civilization that we know depends more on these new sources of power than most of us are prepared to believe. That revolution has all come about without great display but on a grand scale concentrated largely in the last dozen years.

Some few have spent major portions of their lives in this development. They have brought the science of Geology out of the laboratories and off the library shelves and put it to constructive work. We have found it capable of vital practical service and are enthusiastic over that accomplishment.

Therefore tonight I speak in the interest of this small army of men—highly trained, serious-minded, and inventive men—whose chief claim to credit rests in a record of useful public service and whose chief effort is devoted to ways of using for the common good something from the great clutter of accumulated factual knowledge, which, for the most part, is of no consequence whatever until someone discovers what it is good for.

Although it is hardly in my province of discussion, I suspect that there is little difference in the quality of these men as compared with others of less definite practical purpose. It is their business also to discover and interpret and use factual data in any way they choose for whatever results they may yield. Usually they yield more data of the same kind but sometimes they lead to the discovery of a new strain of evidence not clearly distinguished before; and yet again, though not very frequently, the search uncovers entirely new meaning and new practical application. Thus it happens that the principles of the science of Geology are tried out against engineering need.

Perhaps brief further explanation as to the nature of this field and why it has made a place for itself would be in order. The science of Geology has to do primarily with the origin of the features of the Earth, what they are made of, and the changes that they are capable of undergoing. It is particularly concerned with how the Earth has come to be the way it is and with the order of events; with the forces that are resident in the Earth and that affect it from outer space; with the hidden power resident in its material; the agents that perform miracles of transformation and the processes concerned with them. They all belong to this very comprehensive science that we call Geology. It is the same both in content and operation when applied to engineering as when used for any other purpose. The principles are precisely the same, but the uses or objectives vary. The specialistic character of particular situations shifts from one project to another, and as a consequence each succeeding case involves new questions. No two are precisely the same, and an occasional one may not have been encountered in previous experience. Often both the geology and the engineering problem are unfamiliar, and the set-up is absolutely new. But the principles are not new and the elements of the practical problem are not new, and that is the salvation of both the engineer and the geologist, for if they can work with principles their independence and final success are assured.

Although the range of geology likely to be encountered in engineering works is almost as wide as the science itself, by all means the most important problems come in the fields of petrology, structural and dynamic geology, physiography, water content and behavior, and the natural distributions of common minerals and rocks. The individual questions are too numerous and varied to attempt a summary in this address. The most frequent ones are for classification of unfamiliar mineral and rock material, explanation of reason for special physical condition, and interpretation of field exploration. There are endless discussions of origins and meanings and practical significance and the bearing of these features on design or plans and on method of construc-

tion. The most insistent specialistic requirements have to do with strength, stability, expectable effects of changed conditions imposed by construction, and on durability.

The general range is not formidable, but the detail is almost endless. Understanding is the one thing sought by everyone. If one can throw light on the local situation, toward better understanding of its character or its expectable behavior or its bearing on the undertaking at hand, he will be acceptable in any company of engineers.

Since the building of such works has come to be a more or less joint interest of the engineer and the geologist, with few other interfering associates, perhaps something more searching might be said about the characteristics of these men.

The engineer is an aristocrat among applied science men. In his special field he asks no favors. He has been accustomed to responsibility for everything from time beyond counting. If construction was called for, he took the contract. If materials were to be used, he used them. If difficulties were to be overcome, he overcame them. If conditions needed treatment, he treated them. If structures were to be built despite difficulties, he built them. He is competent and constructive beyond most other men. He has confidence in himself and he revels in responsibility. Except for him—thousands upon thousands of him—there would be no great public works. He invents them, he maintains them, and he ought to get the credit for building them.

But not many such men have geological knowledge, and fewer still have a critical working specialistic familiarity with the ground on which their structures rest. The science of Geology has become increasingly specialistic, and the engineer has not kept up. This is the geologist's chance. With his new technique he is able to discover factual points and suggestive evidence that would be wholly overlooked except for his trained eye. But he must not invade the rightful province of the engineer. If he does, no excuse will go. It is still the engineer's privilege to say what to do rather than the geologist's, no matter how experienced he may be. To analyze a situation, to interpret local conditions, and to advise as to their significance is the geologist's province, for there he is on his own ground, but to make use of it in design and plan and contract and construction is for the engineer.

If Geology, as a science, and engineering had set out together on equal terms, one should have to conclude that the engineer had become an expert aggressor, for he appears to own everything. The fact is, however, that he was on the ground first. He was engaged in construction of public works before the geologist discovered what it was all about. He used construction materials before either of them knew what they

were. So the whole realm belonged to the engineer. It was his by right of using. From the time of William Smith nearly to now that responsibility has been the same. The engineer stood for his own brand of geology because the early trend in that science showed little interest in such unspectacular service as that of the engineer. To this day the common attitude is much the same. Only of late has the geologist claimed his share of this field way out on the dim border of his science.

Probably in no other field has it been as difficult to establish a legitimate claim to joint interest. The engineer controls the works. The only thing that makes any impression on him is ability to make worth-while contribution to better understanding of the job. Whatever he needs he assumes is his by right of professional inheritance in addition to public demand and utility. For similar reasons it is unthinkable to him that the building of a structure should be ordered without providing authorization to take over whatever space and supply are necessary. If it is for sale he will buy it; if his ordinary encroachment is resisted he will capture it through condemnation proceedings. Whatever it is and however it behaves, no matter what condition it is in, all becomes part of his problem.

He has had such things to do since earliest time without much help. He did not know, and he did not bother to learn, that there had come into his realm in later years other men who, despite the long experience of his profession, knew more than he about these construction materials and field conditions and the changes that they have undergone and what they mean.

By and by, however, he did discover, partly through bitter experience, that the work could be done with fewer interruptions from surprise discovery or unexpected difficulty if he knew more about the ground, and that frequently serious trouble could have been entirely avoided if there had been competent geological advice in the beginning. Furthermore, he found that these avoidances tended to reduce expense so the new service grew in favor all the more rapidly because it was more economical. This is one of the fundamental principles of the engineering profession—that of greater economy—and now that it was involved he took notice at once. With that last hurdle its practical value had been proven, and from that point on there came to be much higher regard for the strange man with the hammer and the clinometer and the magnifying glass, who could look into the ground and see more there than anyone else could imagine. Thus practical geology emerged and in time was christened Engineering Geology to give it standing and practical content.

It is not at all difficult to see that a mine must have much to do with geology for its very life depends on the resources of the ground and ways

of finding and recovering them. That dependence is so plain that no one can miss it. But the product of the civil engineer is commonly a structure that attracts attention to itself and on its own account rather than emphasizing its relation to and dependence on the ground. That is especially true of a great building or a bridge and to some extent a dam or even a power plant. But all these works rest upon or reach into the earth beneath and depend on its resources for building material. Unless they are adjusted to the conditions found there, success is to that extent endangered. Here is where engineering geology comes into its own and has now become an enormously important factor in the planning and construction of great works, such, for example, as municipal water supply, river and harbor improvement, transportation facilities, flood control, irrigation systems and dams and storage reservoirs and power plants with their transformation of potential energy into actual power.

Buildings of unusual weight or height, structures requiring special stabillty of foundation, or works compelled by other limitations to occupy treacherous ground all come in for the geologist's expert opinion. Bridge piers, highways, and subway and vehicular tunnels all require the judgment of some one who can advise on subsurface conditions. For the most part, of course, and especially in the smaller projects, these steps are largely absorbed by the engineer staff in the routine of standardized field procedures, but, upon occasion, when the demand is extreme or the conditions more difficult or more obscure than usual, the service of the geologist is absolutely essential.

In this kind of service, however, one does not play a lone hand. Out on the marginal fields characterized by co-operation with others all specialistic interests merge into the common effort, and unless they do the best results cannot be attained. Thus it happens that there is seldom special recognition of the individual or of his particular contribution.

Occasionally, however, both the works and the conditions are extraordinary. In such situation brilliant work may be done. Such tasks have been both more numerous and more exacting under the new world conditions and especially in view of the dangers that have broken in upon the new world from the self-destruction of the old.

For many years, as already emphasized, recognition of the importance of geological advisory service, brought about by the building of larger and larger structures and the consequent magnification of hidden dangers, had been growing. But the full measure of such service was not reached until the extraordinary demand came for power connected with defense and preparation for possible war. Now with the actual advent of war this power age has literally exploded in the face of a country ill-prepared for this unbelievably grievous burden.

These two very different interests, Engineering and Applied Geology, are each so enormously varied in content and application that an outsider commonly regards them both as well beyond his comprehension. Even the geologist and the engineer have enough difficulty in understanding each other. But they have to work together because of the fact that numerous elements of both fields are so closely entwined in the final product that it is often impossible to distinguish the line of division between them. Of course that is as it should be. The closer the cooperation the more perfect the resultant product ought to be.

Sometimes the geological work involved in an undertaking is referred to as "Practical Geology" because it is used in the interest of adventures in other fields of endeavor, in this instance, in engineering invention. But it is not a new kind of geology. The geological principles are the same under all demands. Engineering is an art and may be expected to vary in character and expression with the inventiveness of different men. On the other hand, geology is a science, fixed in character and principle, not subject to material modification in fact and meaning, for in geology the sources are always right no matter how many mistakes are made in their interpretation; in engineering the end product is the chief interest no matter how many new starts and changes are made.

The elements or principles of geology may be used in many different ways and for a great variety of special purposes depending upon the needs of other associated interests. Thus it happens that the mining industry has long used such advisory service which has now become a major aid in developing mineral resources. In somewhat like manner the demands of late times for crude oil have led to development of enormous resources of petroleum. And there are yet others, but none of these despite their great importance corresponds to great public works. They are an outgrowth and expression of the development of resources to supply economic or industrial demand. They are vital factors in commercial adventure. To a certain degree those particular undertakings are destructive. Everyone is concerned with removal of valuable substances, and what they take out of the earth is never renewed. Both mining and petroleum extraction are similar in that respect. Cripple Creek can never grow again. Signal Hill is finished, whereas typical public works are distinctly constructive and in contrast have the appearance of permanent improvement.

In applied geology all branches of the science may on occasion be represented, but there are no new kinds except good and bad, and the same may be said of engineering geology. As a matter of fact engineering geology is not a very good name, for it tends to suggest a special kind, whereas it is only the same old kind put to special use.

With greater demand for critical information in all lines that have to do with the earth materials and their behavior the general geologist has come into greater demand also. This result, however, is not wholly due to greater need. It is even to larger degree a product of better geology. Its own principles are better understood. Many of its former speculations have been reduced to rule. The processes of the earth and their products have been more intimately examined so that it is now possible to rely more successfully on isolated bits of evidence to build a working hypothesis that works. And to a still larger degree perhaps the geologist himself has improved. The loose-minded imaginationist has been crowded out. The critical observer and the cautious reasoner have taken his place, and men with special liking for investigation and more or less ability in practical thinking have come into the field.

It has been fashionable in certain quarters to regard applied science service of this sort as of secondary grade compared with that devoted to so-called pure science research. Be that as it may. It is not my purpose to discuss that matter. Even if it is true I am not much interested. It is not my purpose to make extravagant claims for Applied Science, for it needs no defense. It may possibly be, as Professor Pupin used to say, that applied science is the chief difference between the ancient and the modern world. The discovery of how to make use of a discovery may be of greater practical importance than new discoveries if they simply add to the mass of undigested data.

Most of us who take live responsibility in this outlying borderland field are not highly enough trained in engineering to appreciate all the engineer's responsibilities and do not claim superior competence or up-to-dateness in all the specialistic branches of the science of geology. We are not over-versatile even within the limits of geologic science and do not know as much as might be desirable, but we do have a feeling for the so-called practical. We like to find use for the few things we do know and refuse to believe that the ability and willingness to apply what we know are less creditable than the ability to teach it or speculate about it or to carry on further search for more data of the same kind.

There are certain qualifications for such men. One who assumes to advise in a borderland field ought to have a wide range of practical knowledge and a gift for observation and interpretation much above the average. He must be super-critical. He must see more than an engineer can see and be more sure of what it means. He may let his imagination roam over the works without limit except that he must not let it run away with his more orderly judgment. He must reason as carefully as a mathematician and with more variables than a mathematician will tolerate. And he must be right when he gets through. Sixty per cent is

not a passing mark in this field. One must be right. One's advice must have the ring of reasonableness and the soundness of truth. If one does not know the answer he must admit it but determine how to find out. A puzzling situation has to be investigated, but random exploration is out. A geologist who does not know why a test should be made or a boring put down or any other exploratory move made has no business posing as an adviser on important works. One need not know everything. One need not do everything or explore everything himself, but he must analyze the situation and discover the practical elements, if there be any, and see that he finds how they fit into the structure of the problem in hand. If he cannot do that he should not be in this line. Perhaps he should not be in geologic service at all.

Among engineers I believe that to be classified as a geologist is not a very high recommendation. In many organizations any sort of engineer, even a third or fourth rate one, seems to be more highly regarded. Therefore one need not plume himself with a membership button or a diploma. It is only what he can deliver that counts. To gain recognition among his fellows and favor with his superiors in the system he must prove superior quality both in observational keenness and practical sense. Then, if he can picture the situation clearly, either in language or drawing or both, so that everyone, even the dumbest engineer, can understand, he will be accepted and in due time may gain an enviable reputation.

Not all the qualifications for an engineering geologist are found in geological treatises. Some of them have little to do with geologic science. One may have a very broad knowledge of geology and be reasonably competent and yet not gain the attention that one must have if he is to contribute his share in engineering undertakings. It is easy to talk too much and say too little. That alone creates suspicion, and if, in addition, a few unfamiliar words are used, no matter how correct they may be, it often happens that the whole effort is thrown to the winds. Under ordinary conditions no one can be an outstanding success who loads his explanatory contributions with supertechnical terms. A common ground of understanding has to be established, and that is accomplished in large part by using the vernacular as far as it will go.

Most persons follow illustrated explanation more readily than barren description, and no one is more firmly fixed in that preference than the engineer. It gives him opportunity to exercise his love for measuring and the quantitative principle. He revels in plans and profiles and curves and formulas. He will forgive you for a few strange terms, your slight to mathematics, and the crudeness of your drawings if he discovers that your diagrams and cross sections are actually understandable.

He will be interested in a historical account if it helps him better to understand the processes that have brought trouble to his job. But he must be shown that it has. The tendency of the garden variety of geologist to wander off into specialistic side detail, especially lists of long-forgotten fossils and flights of historical fancy, confuses the engineer. One must not offend the singleness of purpose and the directness of the engineer whose lurking fear always is that there are yet other and unknown factors that neither you nor he have uncovered and that these might easily upset all his calculations. One must create confidence and settle his mind. He did not ask to be entertained.

Yes, I know that this is not geologic science, but it is a common-sense way of introducing geology to practising engineers, and, unless some such procedure is followed, it will not be used even if it is offered. A widely known geologist once complained to me that the engineers on a great project paid no attention to his advice. That in itself was not very surprising or unusual but in this case seemed at least to be worth investigating. His advisory report made a manuscript volume so bulky that no busy engineer would take the time to read it, and, if by chance he did, he could not tell what it meant. The engineer was right in ignoring it. He had a right to expect that the mass of factual data would be analyzed and be put in elementary terms with emphasis on their practical bearing. It was perfectly evident in this instance that the situation was still obscure. What to do with it was the advice most needed so that the next step could be taken. But no one could tell from this report what to do next.

If the engineer must discover all the weak points himself, and ask all the questions, the advisory set-up will fail. By the time he discovers what to ask it is generally too late for the answer. The best opportunity to help is gone. One must discover ways to be useful before the need is discovered by everybody else. One must devise ways of clarifying situations that are complex or obscure as soon as or before they appear. If the problem does not solve with the facts in hand, one must be inventive enough to set up a test or an exploratory program that will get the data needed. Then he must explain what it means.

This is no place for a novice. Neither is it a proper place to learn the principles of geologic science or to gain experience at the expense of the job. But it is a good place to use what one does know and it will tax one's best ingenuity to make it acceptably intelligible to the hard-headed, tough-minded devotees of precision that one is sure to meet at every drafting board in every engineering headquarters the world over. These men are veritable fiends for careful work and they are, above all others within my experience, consumed with a feeling of personal responsibility.

Of course the impossible is expected of the geological associate. He is expected to describe in detail what no one else can see. On occasion he will be taken over absolutely new ground with a group of engineers, who know already what it is about, and be expected to reply to questions on which he has had no opportunity to make observations of his own. He is expected to be a sort of petrologic clairvoyant and must manage in some way to carry on despite the handicaps. He must be ready to hold forth in an acceptable manner at dinner the same night and have a program for the morrow. He retires at midnight, exhausted but reasonably content if up to that time no one had discovered how hard he was put to it by their questions and how little he really found out.

Saying too much is one of the most difficult things to avoid. These men have a curious way of recalling precisely what was said, and years after they will repeat it as if it were an oracle, whereas it may have been at the time simply a way of saying nothing at all. Nevertheless it is a poor geologist who cannot see more meaning in the features passed in review than is usually appreciated by these specialists in other fields, and one's contribution is always acceptable if it is reduced to terms of common understanding and is as illuminating as it ought to be.

Of course it is impossible to be always right, but in any case the passing mark must be well up on the scale. In some other kinds of geological work one may be successful if he is right more than half the time. In this engineering service it does not take many blunders to queer one's reputation. It is a dangerous thing even to guess right. One doesn't guess. If a beginner happens to be right it tends to create overconfidence in him both by the geologist himself and by the engineering staff. Thereafter he may be believed, even if he is wrong, and he really becomes an unaccountable risk.

Everywhere among engineers one is faced with the scale and rule. If you show him a drawing he will reach for his rule. They will measure anything. They want to know, whether they need it or not, how deep it is? How far? How long? How much? How strong? What did it cost? The quantitative principle characterizes the typical engineer, and he fits everything to that end. Thus he soon establishes a formula and, that once done, he is satisfied and is likely to assume that his task is finished. The thing he most detests in his friend the geologist is his at-homeness with variables and uncertainties and partially solved questions and elements of no apparent value at all. If an engineer succeeds in measuring a rate or a resistance or a strength on any portion of what seems to him to be a simple formation, he is prone to accept it all and by inserting values in his formula the Q E D is soon accomplished. That is where he needs the seemingly loose-minded geologist to keep him true

to life. The geologist knows that the next sample will not give the same value, but that fact does not distress him in the least. Even if the rock or sample or soil or the major process varies all over the lot, he is still willing to work with it to some practical or semi-practical end.

I keenly recall the shock brought to me, by a telegram from the Chief Engineer of a federal bureau, to the effect that certain samples of granite rock that everyone knew came from the foundation of the Grand Coulee Dam were giving tests below 10,000 pounds. That is about a quarter of the expected strength of such rock, and the inference was that the foundations for the greatest dam in the world were too weak for such an immense structure. Thus suspicion of the whole foundation was aroused. Clearly something was wrong. This discrepancy must be explained. Either special treatment must be devised, or perhaps the site be condemned. A new picture of the local physical situation was thus created. That it could be explained as a very local and understandable feature and the situation be finally accepted seemed impossible at first, but it came to pass. The objectionable condition had to be met, but it did not move the dam or endanger it.

Many of the dangers accompanying the building of large engineering structures are of geological origin and it is one of the chief responsibilities of the geologist to point this out in time to avoid accident. It is one of the most difficult duties. The commonest danger, of course, is from falling rock in excavations such as those for foundations in the open, from the roof in rock tunnels, and from caving or running ground charged with water and mud. Such accidents are not rare. Some of them were formerly considered "acts of God" and simply had to be accepted without complaint. They were originally, I suppose, classified in that category chiefly because of inability to predict or explain them. Some of them, of course, are likely to baffle the best advisory service; but the great majority of potential accidents of this kind are now avoided by securing advance knowledge of the local physical situation and by seasoned judgment and more liberal use of protective measures. Much of the old fear is gone because the reasons for these conditions are better understood. So the mystery about them has been largely dispelled. But the strongest men are unnerved when the solid rock begins to send out distress signals that mark its instability, and sharp-edged slabs split off the bare rock walls as if they were something alive. Great care is taken, however, and large expense is sometimes involved in providing protection to the workmen under these conditions.

In occasional places, particularly in tunnels, where the native rock is crushed and decayed and watercharged, the whole loose and softened mass may break into the excavation suddenly enough to trap the men.

These dangers cannot always be detected in time, but in closely watched work actual tragedy is extremely rare. The geologist, as well as the engineer, is always on the alert so that provision may be made against surprise. Complete surprise is necessarily a reflection on the geologist, for he ought to discover evidence of danger. Such accidents are seldom his fault alone, for the actual task of providing protection rests on the engineer. Such provision costs more, sometimes a great deal more; it takes more time, and time is money. Furthermore, there is always the suspicion that the extra protection called for may not be necessary. Consequently, if the work proceeds for a while without renewed threat, precautionary measures tend to be discredited, and undue risk is tolerated until another so-called accident happens.

This responsibility is one of the most trying and discouraging questions connected with construction where large excavations are involved. Much depends on co-operation down to the last workman. Much more rests on good judgment of those in charge and the kind of balance that comes with experience. In this connection one soon discovers the shortcomings of the average beginner. In fact it sometimes happens that the greatest danger is the so-called geologist himself rather than the geological conditions. If he is timid, he is likely to be over-suspicious and correspondingly over-expensive. On the other hand, if he is venturesome he may be too incautious to be of any help, and equally expensive or dangerous on that account. It may very well be better to have no geologist at all than an incompetent one. At least those who do the work and face such dangers as there are, or assume the final responsibility, should not be misled.

A still more discouraging situation frequently arises in the transition stages of an organization where realization of the need of geology is new. In such cases it too commonly happens that almost anyone that can be spared from the regular line of engineering operations, especially if he has had a short course in geology or "has read a book," is given the job. Such service is worse than useless. Such an adviser is actually a menace to the job. Yet important projects have been treated that way, and to this day those in charge do not realize that their so-called geologist was dangerously ignorant of what it is all about.

As a matter of fact the engineer of forty years ago still believed that the little geology he needed he could do himself. A real geologist or specialist in one of the branches of the subject was seldom called even for consultation unless there was an accident to be investigated and explained. Only a few men enjoyed even occasional consultation privilege. As far as I have been able to learn, not a single geologist had at that time a place on any staff responsible for the construction of such

works. As pointed out before, there had never been a place for the geologist on any Board or Commission charged with such responsibility. That situation has now been revolutionized, and in that development it has been my good fortune to take part.

Not since the time of William Smith, who combined his geology with his own engineering, until recently has there been so close a tie between geology and engineering as there is now. In that time geology has emerged as a science, but instead of being included bodily in the field of engineering where some of it began, it has its own body of principles and a great variety of specialistic interests.

In this particular field of Engineering Geology there is not much at which to marvel. There are no bonanzas—no fortunes made overnight. Nevertheless these are some of the most useful undertakings in which men may engage. In them the scientifically trained person uses his knowledge and skill in improvement of his physical surroundings. These are the works marking the progress of material civilization and magnifying the limited competence of man's bare hands. They are literally fountains of power—perhaps in this present emergency the power that is to save the world. In a world seemingly bent on self-destruction, at least these adventures face toward the future and stand out as if to promise better times in a more constructive world. So I claim a place of honor for these men who spend their lives in devising new ways of using their specialistic knowledge and experience and ingenuity for more effective public works and for the greater comfort and safety of men and women everywhere.

GEOLOGICAL SOCIETY PRESIDENTIAL ADDRESSES

Date	*Name*	*Title*
1889	James Hall	Early History of American geology and geologists.
1892	G. K. Gilbert	Continental problems.
1893	Sir William J. Dawson	Some recent discussions in geology.
1894	T. C. Chamberlin	Recent glacial studies in Greenland.
1895	N. S. Shaler	Relations of geologic science to education.
1896	Joseph LeConte	Earthcrust movements and their causes.
1897	Edward Orton	Geological probabilities as to petroleum.
1898	J. J. Stevenson	Our Society.
1899	B. K. Emerson	The tetrahedral earth and zone of the intercontinental seas.
1900	G. M. Dawson	Geological Record of the Rocky Mountain region in Canada.
1901	Charles D. Walcott	Outlook of the geologist in America.
1902	Newton H. Winchell	Was man in America in the Glacial period.
1903	S. F. Emmons	Theories of ore deposition historically considered.
1904	John C. Branner	Stone reefs on the northeast coast of Brazil.
1905	Raphael Pumpelly	Independent evolution of oases and civilizations.
1906	Israel C. Russell	Concentration as a geological principle.
1907	Charles R. Van Hise	The problem of the pre-Cambrian.
1908	Samuel Calvin	Present phase of the Pleistocene problem in Iowa.

Date	*Name*	*Title*
1910	Arnold Hague	Origin of the thermal waters in the Yellowstone National Park.
1911	W. M. Davis	The relations of geography to geology.
1912	H. L. Fairchild	Pleistocene formations of New York State.
1913	Eugene A. Smith	Pioneers in Gulf coastal plain geology.
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1915	Arthur P. Coleman	Dry land in geology.
1916	John M. Clarke	The philosophy of geology and the order of the state.
1917	Frank D. Adams	Experiment in geology.
1918	Whitman Cross	Geology in the World War and after.
1919	John C. Merriam	Earth sciences as the background of history.
1920	I. C. White	Important epochs in the history of petroleum and natural gas.
1921	James F. Kemp	After-effects of igneous intrusion.
1922	Charles Schuchert	Sites and nature of the North American geosynclines.
1923	David White	Gravity observations from the standpoint of local geology.
1924	Waldemar Lindgren	Metasomatism.
1925	William B. Scott	Geological climates.
1926	Andrew C. Lawson	Folded mountains and isostasy.
1927	Arthur Keith	Structural symmetry of North America.
1928	Bailey Willis	Continental genesis.
1929	Heinrich Ries	Some problems of the non-metallics.
1930	R. A. F. Penrose, Jr.	Geology as an agent in human welfare.
1931	Alfred C. Lane	Eutopotropism.
1932	Reginald A. Daly	The depths of the earth.
1933	C. K. Leith	The pre-Cambrian.
1934	W. H. Collins	Geology and literature.
1935	Nevin M. Fenneman	Cyclic and non-cyclic aspects of erosion.
1936	W. C. Mendenhall	Evolution and present status of geology in North America.
1937	Charles Palache	Present trends in mineralogy.
1938	Arthur L. Day	The hot-spring problem.
1939	T. Wayland Vaughan	Ecology of Modern marine organisms with reference to paleogeography.
1940	Eliot Blackwelder	Science and human prospects.

COLUMBIA UNIVERSITY, NEW YORK, N. Y.

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CORRELATION OF THE SILURIAN FORMATIONS OF NORTH AMERICA

BY CHARLES K. SWARTZ *(Chairman)*, F. J. ALCOCK, CHARLES BUTTS, G. H. CHADWICK, E. R. CUMINGS, C. E. DECKER, G. M. EHLERS, A. F. FOERSTE,* T. GILLETTE, E. M. KINDLE,* EDWIN KIRK, S. A. NORTHROP, W. F. PROUTY, T. E. SAVAGE, R. R. SHROCK, F. M. SWARTZ, W. H. TWENHOFEL, AND M. Y. WILLIAMS.

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ILLUSTRATION

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1. Correlation of the Silurian formations of North America (Chart 3 of series). 538

INTRODUCTION

This is Number 3 of a series of correlation charts prepared under the auspices of the Committee of Stratigraphy of the National Research Council (Dunbar, 1942, p. 429-434). It was compiled by a subcommittee on the Silurian system.

Each member of the subcommittee has furnished, and is responsible for, the correlations suggested in the columns bearing his name and has provided or approved the annotations cited in his columns.[1]

The correlations of the Silurian deposits of northwestern Greenland with British formations are from the reports of Lauge Koch (1929, p. 237-242) and Chr. Poulsen (1934, p. 44).

ANNOTATIONS

1. The Medinan of Vanuxem and Hall was shown by Grabau and others to include, at its base, the Queenston shale of Richmond age, here referred to the Upper Ordovician. Ulrich, Bassler, and the New York Geological Survey use the term in its original sense to include the Queenston shale which they consider Silurian. Many, following

* Deceased.

[1] The annotations are numbered to correspond with the numerals on the chart.

Grabau, restrict the Medinan to the beds above the Queenston and below the Clinton.

J. M. Clarke proposed the term Albion for the Medinan beds lying above the Queenston shale (Ulrich, 1913, p. 26-49; 1914, p. 625-652). This usage has been adopted by the Committee on Geologic Names of the U. S. Geological Survey and is followed here.

2. The Pike Arm Shale, Goldson conglomerate, and Botwood sandstone are exposed in Notre Dame Bay, the Natlins Cove formation in White Bay.

3. Northrop (1939, p. 102, 111-114) correlates the Chaleur series of Quebec with formations of England and Wales from the Upper Llandovery to Aymestry, inclusive, and regards the Aymestry and Lower Ludlow as upper Niagaran. He correlates Indian Point and West Point with Aymestry; Bouleaux with Lower Ludlow; Gascons and La Vieille with Wenlock and Woolhope; Anse Cascon and Clemville with Upper Llandovery.

4. The systematic relations of the Keyser limestone are insecure. It has long been recognized that the Keyser is a correlate of the beds of southeastern New York and northern New Jersey, there identified as the Decker, Rondout, and Manlius formations, inclusive.

Ulrich (1911, p. 590-591), recognizing the Lower Devonian elements of the Keyser fauna, considered the Keyser to be Lower Devonian. He believed (Swartz, 1913, p. 115, footnote 2; 116-117) that the Manlius of the region under consideration differs in age from that of the type area in central New York, the former being Lower Devonian, the latter Silurian. Later investigations lend weight to the view, long held by the geologists of New York, that the Manlius of southeastern New York is approximately of the same age as the typical Manlius, which has been considered Silurian.

5. Absent in south.

6. The McKenzie is made Cayugan by Ulrich and Bassler (1923a, p. 245-247) and others.

7. The term Chrysler was proposed by Chadwick for beds here called the Rondout. He states (personal communication):

> "The beds called Rondout in this column include more than those to which the name has latterly been confined in the type region in the east, but agree with those to which the name was originally applied there; hence Chadwick now considers his term Chrysler to be superfluous."

8. Chadwick and Ehlers, following Ulrich, include the Guelph in the Lockport group. Cumings restricts the latter term to the beds below the Guelph. The typical Guelph fauna has not been observed east of Wayne County, New York. Whether this means a hiatus or simply a change of facies cannot here be affirmed.

9. The Lockport limestone was defined by James Hall, but no upper limit was given by him in the type area. About 220 feet of limestone was shown by M. Y. Williams to lie between the Rochester and Cayugan shales in the vicinity of Niagara Falls. Only the lower 120 feet is there exposed, the overlying strata being concealed, presumably, in the rapids above the Falls.

Two interpretations have been placed upon the upper limit of the Lockport: (1) Ulrich, followed by Goldring and others, has extended the term Lockport to include all the limestones and faunas lying between the Rochester and Cayugan shales, including the beds containing the Guelph facies; (2) M. Y. Williams, Cumings, and others separate the limestones into two formations—the Lockport below, terminated by the Eramosa beds, and the Guelph above. According to this view (Williams, 1919, p. 71) the lower 80 feet, approximately, of limestone at Niagara Falls is Lockport, the upper 140 feet (about) is Guelph. The Guelph is thought to have a distinctive fauna and lithology, although certain Guelph precursors appear near the top of the Lockport as thus defined. The term Lockport limestone is here used in the latter sense.

10. The term Willowvale shale is here proposed by Gillette for shales representing the Williamson and Irondequoit intervals of western New York.

11. Chadwick places the major breaks in the Silurian sequence of western New York at disconformities: (1) between the Rochester and Lockport-Guelph, and (2) between the Vernon and Syracuse-Camillus. He sees no break between the Albion and Clinton, or between the Lockport-Guelph and Vernon, where present lines are drawn.

12. Many unite the Decew limestone with the Lockport group.

13. Chadwick (1918, p. 353-355) restricts the Clinton group to the beds below the Rochester shale, believing that the latter is absent from the typical Clinton and that the Herkimer sandstone is of Irondequoit, not Rochester, age.

14. Gillette reports the occurrence of *Mastigobolbina typus* in the Irondequoit limestone of New York, indicating that the Irondequoit is older than the Keefer sandstone with which it has been correlated by various geologists.

15. Ulrich and Bassler (1923b, p. 327-328) and others consider the Thorold sandstone to be the initial deposit of the Clinton group. Chadwick suggests that a sandstone lying beneath the Maplewood shale at Rochester, New York, named by him the Kodak sandstone, is the initial deposit of the Clinton of that area. He considers it distinct from the type Thorold and refers the latter to the top of the Medina.

16. The name Cabot Head was first proposed by Grabau (1913, p. 438, 460) for the red and gray Cataract shales and included dolomites of the mainland of Ontario. Williams (1919, p. 32) later extended its application to embrace the Cataract shales of southwestern Ontario and the Georgian Bay region. He included in it the Dyer Bay and St. Edmund dolomites, interpreting the latter as local lentils, of small lateral extent, in the shale.

Cumings and Ehlers regard the Dyer Bay and St. Edmund dolomites as the eastern feather edges of important formations which are well developed westward, and they restrict the Cabot Head to the shale above the Manitoulin and below the Dyer Bay dolomites. They also correlate the St. Edmund with the Hendricks dolomite of Michigan which is of post-Albion age.

17. The Silurian strata of southern Ontario were deposited in two basins, which are divided by an anticlinal axis. This axis passes southwestward, approximately, through the village of Cataract, situated near the western end of Lake Ontario.

The formations named in this column are found north and west of the Cataract axis. The Silurian formations found in the basin south and east of this axis are largely those of western New York. The latter cross the Niagara River into southern Ontario without essential change, as shown by M. Y. Williams (1919) and others. A fuller title for the column headed Western New York in this chart might, hence, well be "Western New York and adjacent parts of Southern Ontario."

18. Wingfield shale. This name will be proposed by Mr. Harold Way.

19. The Dyer Bay limestone is referred to the Middle Clinton by Ulrich and Bassler (1923b, p. 267, 334-337).

20. Savage correlates the lower part of the Byron with the Brassfield limestone.

21. Savage correlates the Mayville dolomite with the Edgewood. Ulrich and Bassler (1923b, p. 334-337) correlate it with the Middle Clinton.

22. The Waukesha limestone of southeastern Wisconsin was named by Lapham, who defined it as lying immediately beneath the Racine dolomite. Its lower limit was not fixed by him and has been placed by other authors at various horizons from the base of the Cordell to the base of the Byron. The term, hence, lacks precision and in Wisconsin has been replaced by the names here used.

Savage proposes the name Bellwood dolomite for the beds formerly called the Waukesha dolomite in northeastern Illinois. They are well exposed in the vicinity of Bellwood, Cook County, Illinois, from which locality they receive their name.

Savage also proposes the name Cordova dolomite for the beds formerly called the Waukesha dolomite in northwestern Illinois and Iowa. They are well exposed in the large quarry of the U. S. Gypsum Company, 1½ miles south of Cordova, Rock Island County, Illinois.

23. Many geologists make the Brassfield limestone Upper Albion.

24. The Henryhouse shale is correlated by Decker with the Lower Ludlow of Great Britain by means of graptolites. The American relations are less precise. Three species are common to the Henryhouse and the Brownsport formations of western Tennessee.

25. Decker correlates the lower part of the Blaylock sandstone of Arkansas with the upper part of the Middle and the lower part of the Upper Birkhill of Scotland by means of graptolites. Some students correlate the lower part of the Blaylock with the Brassfield limestone.

26. The Silurian strata exposed in the vicinity of Lake Winnipeg in southern Manitoba were named the Stonewall series by Kindle (1914, p. 249). The studies of the author have shown that the Silurian formations previously described in the Hudson Bay region of northern Ontario (except the Attawapiskat) can be recognized so clearly by their faunas in southern Manitoba that he proposes to use the Hudson Bay names for strata of the latter region also, as is done in this chart. The evidence upon which these conclusions rest will be presented in a forthcoming publication.

27. Ehlers makes the Severn River and Ekwan River limestones of Clinton age, correlating them with the Hendricks dolomite of Michigan. He considers the Attawapiskat coral reef but little younger.

28. The name North Nahanna River dolomite was proposed by E. M. Kindle (1936, p. 14-15) for beds earlier designated by him the Lone Mountain formation, in the Mackenzie River valley. Hague's Lone Mountain limestone of Nevada had priority in date of publication over Kindle's earlier name and apparently designates a bed of different Silurian horizon.

29. Foerste (1929, p. 69) suggests the possible correlation of the *Lissatrypa phoca* fauna of the Arctic region with the fauna of the Keyser limestone of the Appalachian region.

30. A Niagaran fauna from the northernmost part of Southampton Island, studied by C. Teichert, includes *Brachyprion* cf. *philomelum* (Billings), *Camarotoechia neglecta* (Hall), *Leperditia phaseolus* (Hisinger), and other Niagaran species. (*See* Kindle, 1939, p. 191.)

31. Northrop correlates the Chaleur series of Quebec, which he regards Niagaran, with the formations of England and Wales from the Upper Llandovery to the Aymestry, inclusive. (*See* annotation 3.)

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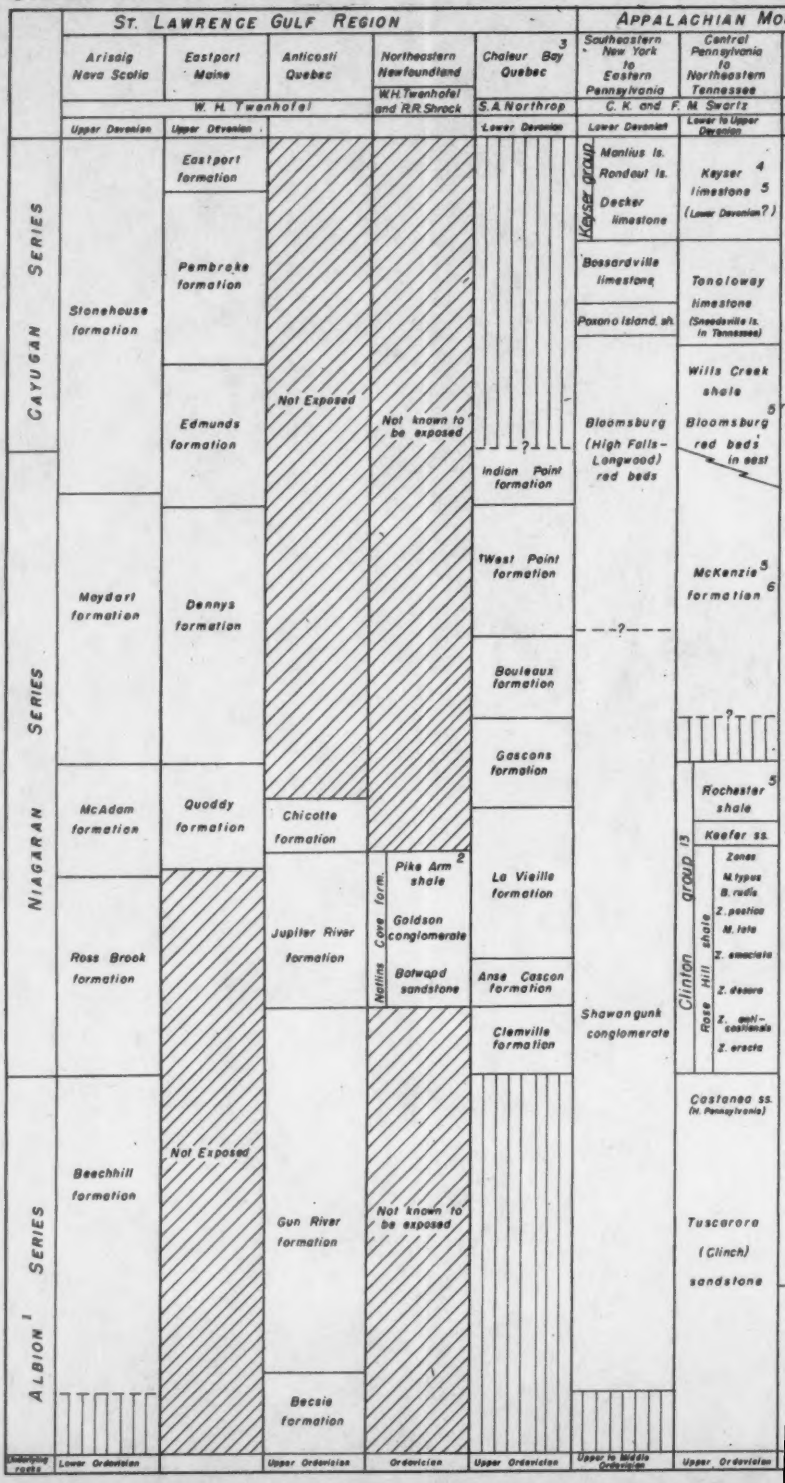

ST. LAWRENCE GULF REGION
APPALACHIAN MO
Arisaig Nova Scotia
Eastport Maine
Anticosti Quebec
Northeastern Newfoundland
Chaleur Bay 3 Quebec
Southeastern New York to Eastern Pennsylvania
Central Pennsylvania to Northeastern Tennessee
W. H. Twenhofel
W.H. Twenhofel and R.R. Shrock
S.A. Northrop
C. K. and F. M. Swartz
Upper Devonian
Upper Devonian
Lower Devonian
Lower Devonian
Lower to Upper Devonian
CAYUGAN SERIES
NIAGARAN SERIES
ALBION 1 SERIES
Eastport formation
Pembroke formation
Edmunds formation
Stonehouse formation
Not Exposed
Not known to be exposed
Indian Point formation
Meydort formation
Dennys formation
West Point formation
Bouleaux formation
Gascons formation
McAdam formation
Quoddy formation
Chicotte formation
La Vieille formation
Ross Brook formation
Jupiter River formation
Nothing Cove form.
Pike Arm shale 2
Goldson conglomerate
Botwood sandstone
Anse Cascon formation
Clemville formation
Beechhill formation
Not Exposed
Gun River formation
Not known to be exposed
Becsie formation
Manlius ls.
Rondout ls.
Decker limestone
Kayser group
Kayser limestone 4
(Lower Devonian?)
Bossardville limestone
Tonoloway limestone
(Snoddyville ls. in Tennessee)
Poxono Island sh.
Wills Creek shale
Bloomsburg red beds 5
Bloomsburg (High Falls–Longwood) red beds
McKenzie formation 5 6
Rochester shale 5
Keefer ss.
Clinton group 13
Zones
M. typus
B. rudis
Z. postica
M. tota
Z. emaciata
Z. desora
Z. amblicostalis
Z. erecta
Rose Hill shale
Shawangunk conglomerate
Castanea ss.
(N. Pennsylvania)
Tuscarora (Clinch) sandstone
Underlying rocks
Lower Ordovician
Upper Ordovician
Ordovician
Upper Ordovician
Upper to Middle Ordovician
Upper Ordovician

Chart No. 3 - CORRELATI

By Charles K. Swartz *(Chairman)*, F. J. Alc
E. M. Kindle, Edwin Kirk. S. A. North

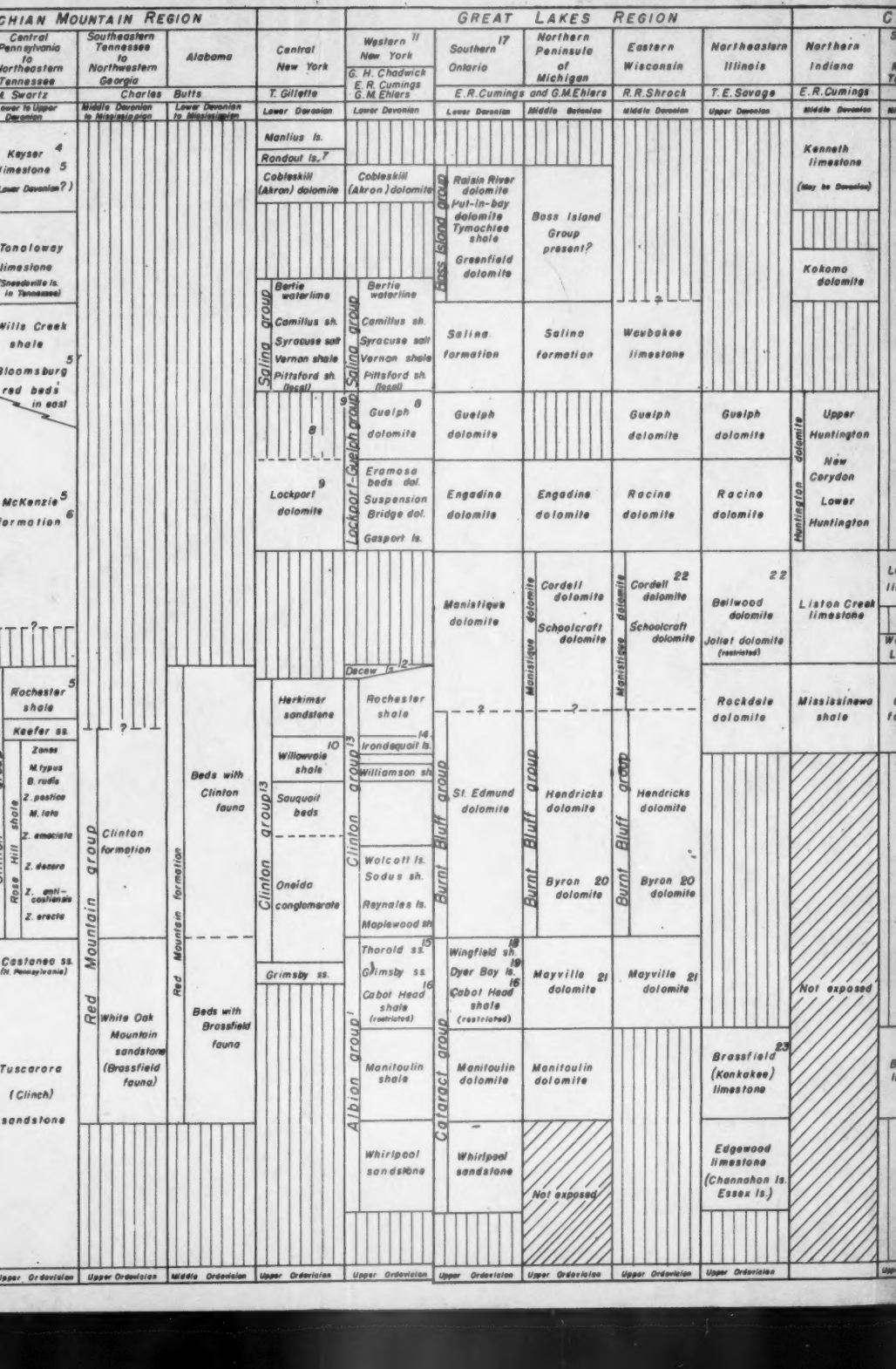
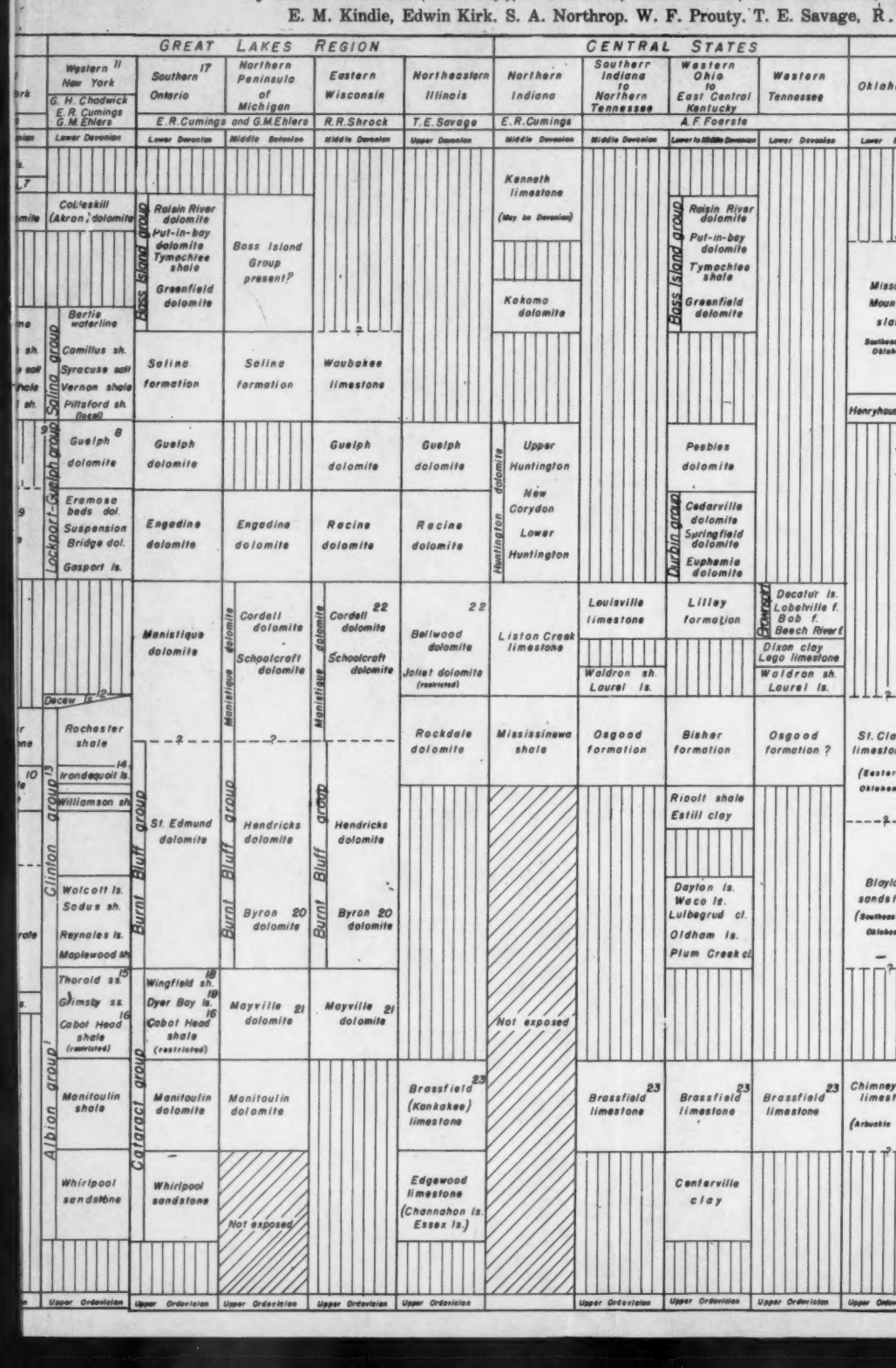


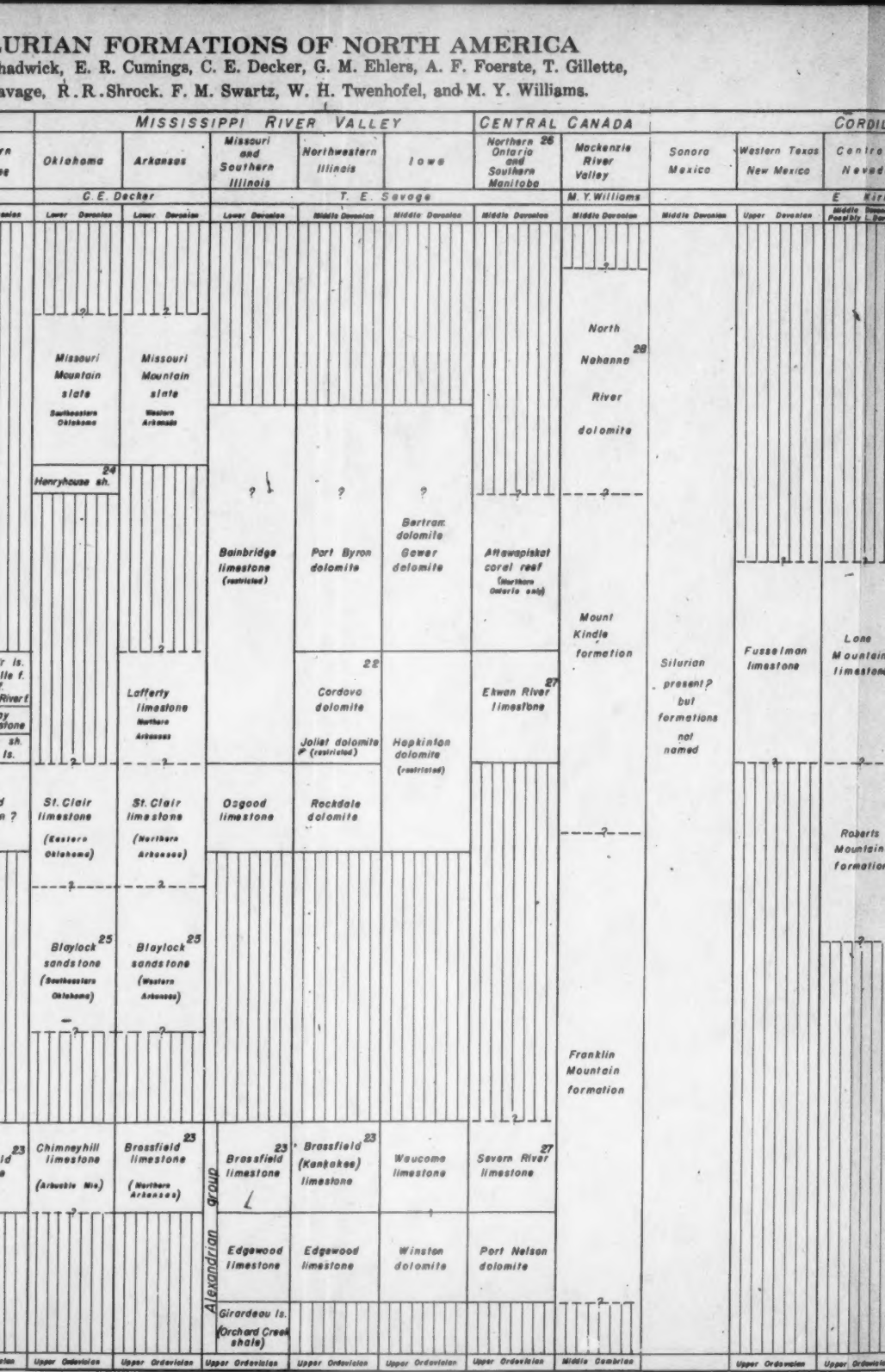
Chart No. 3 - CORRELATION OF THE SILURIAN

By Charles K. Swartz *(Chairman)*, F. J. Alcock, Charles Butts, G. H. Chadwick, E. M. Kindle, Edwin Kirk. S. A. Northrop. W. F. Prouty. T. E. Savage, R.



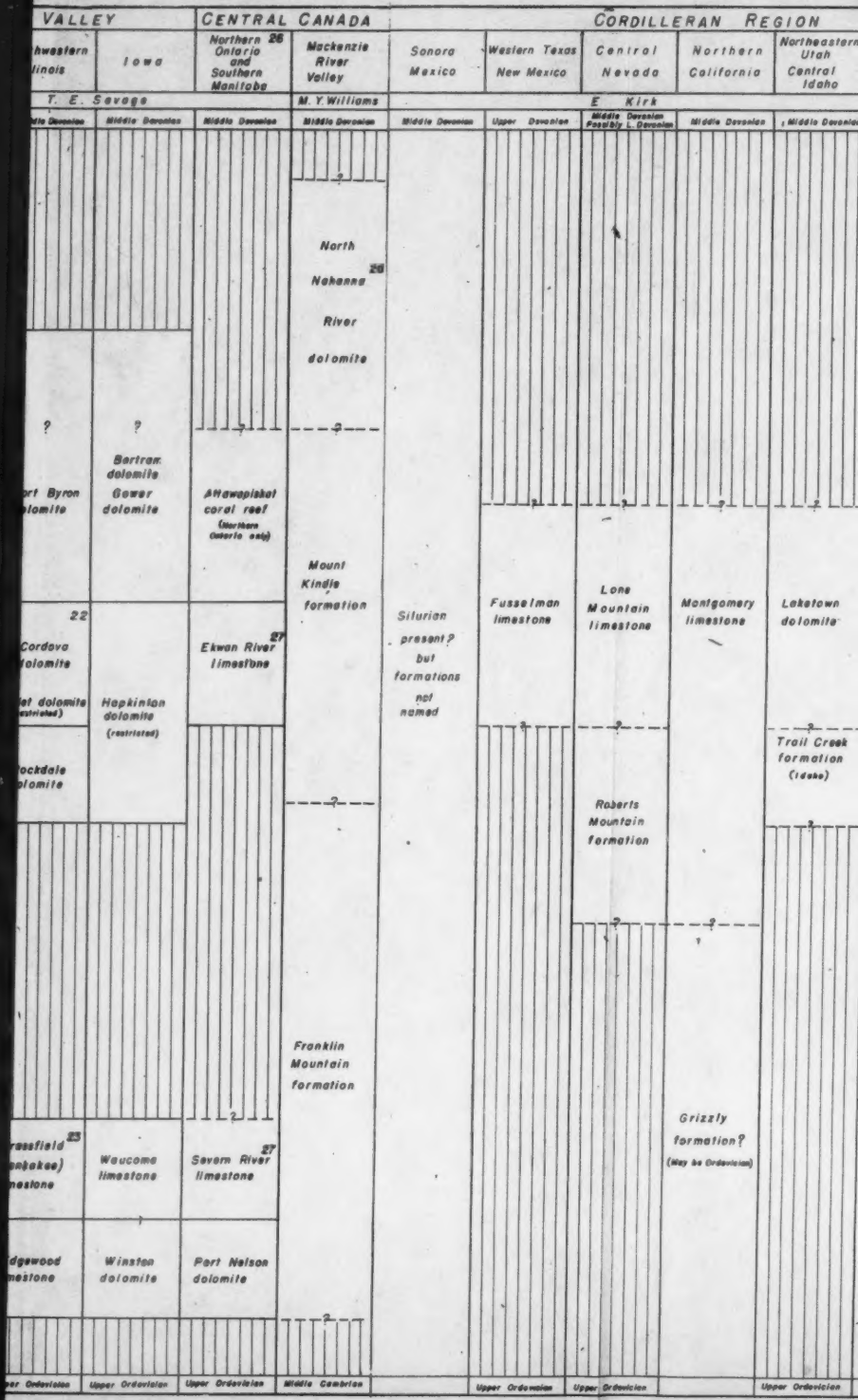
URIAN FORMATIONS OF NORTH AMERICA

hadwick, E. R. Cumings, C. E. Decker, G. M. Ehlers, A. F. Foerste, T. Gillette,
avage, R. R. Shrock. F. M. Swartz, W. H. Twenhofel, and M. Y. Williams.



NORTH AMERICA

M. Ehlers, A. F. Foerste, T. Gillette,
L. Twenhofel, and M. Y. Williams.


VALLEY
CENTRAL CANADA
CORDILLERAN REGION
hwestern Illinois
Iowa
Northern Ontario and Southern Manitoba 26
Mackenzie River Valley
Sonora Mexico
Western Texas New Mexico
Central Nevada
Northern California
Northeastern Utah Central Idaho
T. E. Savage
M. Y. Williams
E. Kirk
Middle Devonian
Middle Devonian
Middle Devonian
Middle Devonian
Middle Devonian
Upper Devonian
Middle Devonian Possibly L. Devonian
Middle Devonian
Middle Devonian
North Nahanni 28 River dolomite
?
?
?
?
?
?
?
?
?
?
Bertram dolomite
Gower dolomite
Attawapiskat coral reef (Northern Ontario only)
Mount Kindle formation
Silurian - present? but formations not named
Fusselman limestone
Lone Mountain limestone
Montgomery limestone
Laketown dolomite
rt Byron lomite
22
Cordova lomite
et dolomite estricted)
Hopkinton dolomite (restricted)
Ekwan River 27 limestone
Trail Creek formation (Idaho)
ockdale lomite
Roberts Mountain formation
Franklin Mountain formation
ossfield 23 nekake) mestone
Waucoma limestone
Severn River 27 limestone
Grizzly formation? (May be Ordovician)
dgewood mestone
Winston dolomite
Port Nelson dolomite
?
?
?
?
?
?
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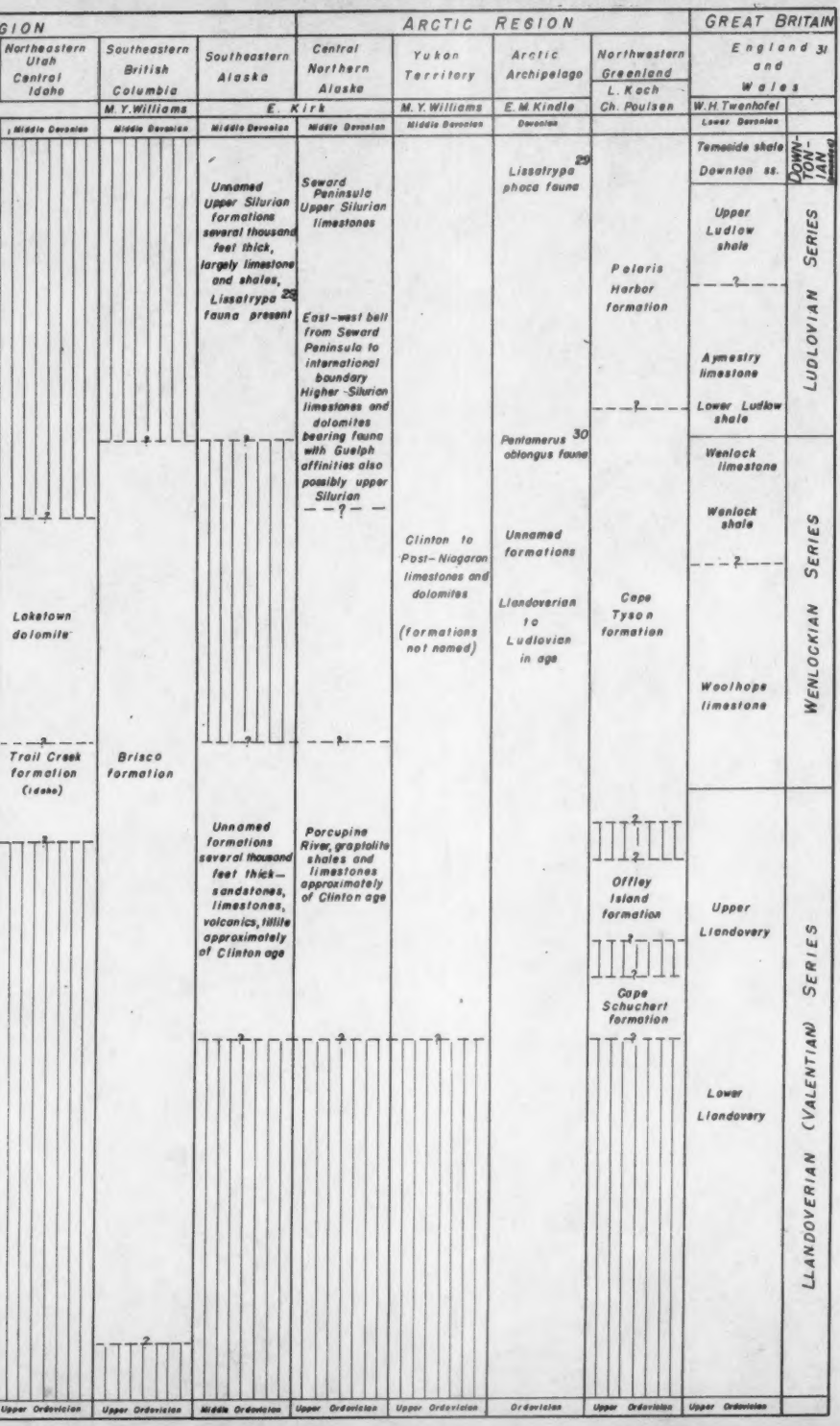
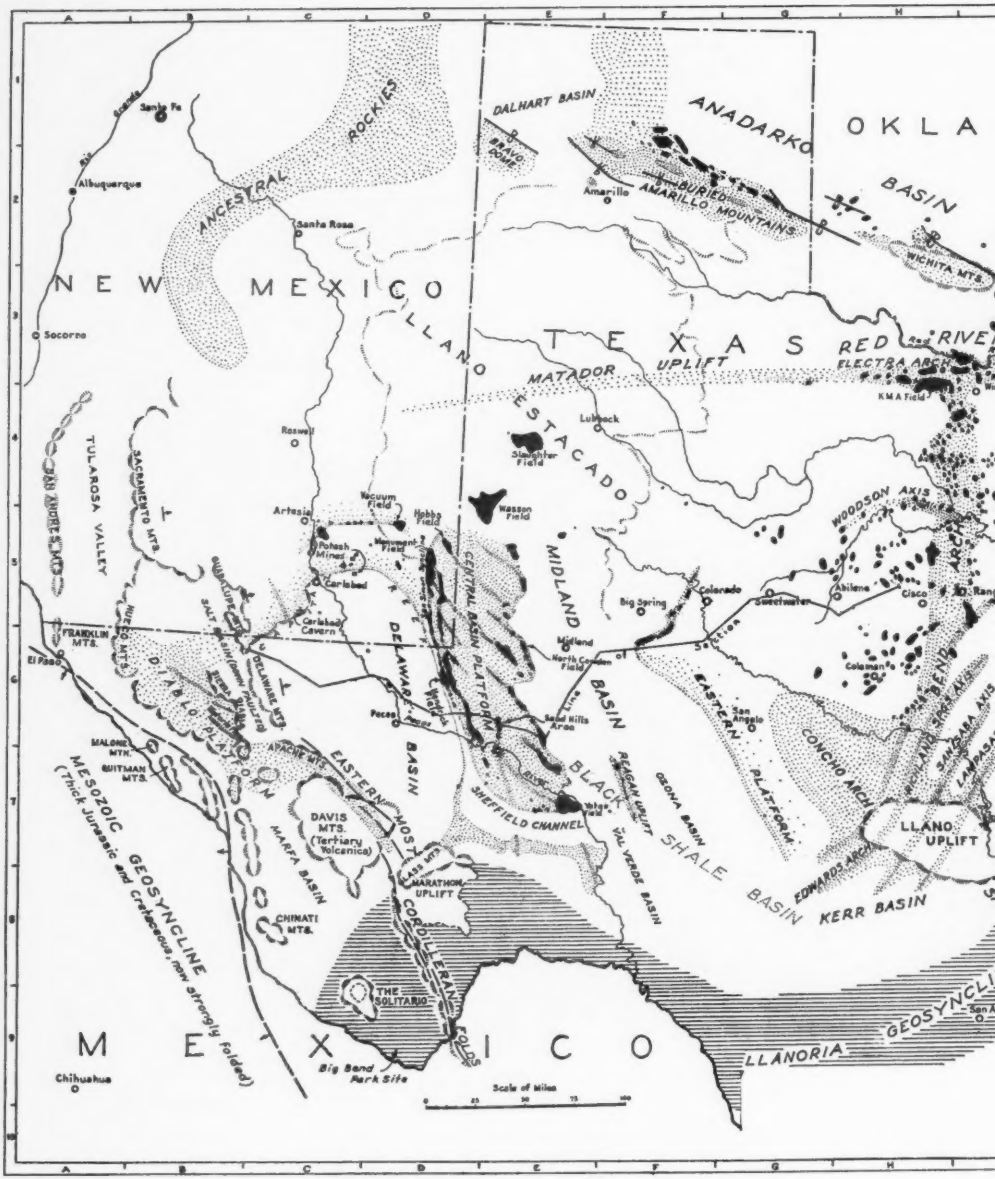
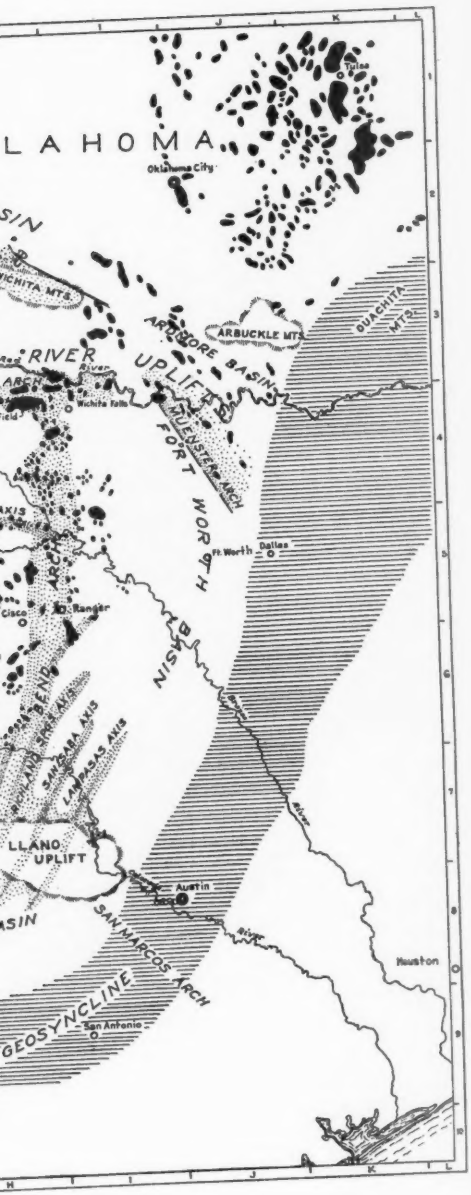
?
?

Prepared under the auspices of the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, *Chairman*.





REGIONAL TECTONIC MAP


LAHOMA
Tulsa
Oklahoma City
ARBUCKLE MTS.
OUACHITA MTS.
RIVER UPLIFT
ARKOMA BASIN
Wichita Falls
FORT WORTH BASIN
Fort Worth
Dallas
Ranger
Cisco
LLANO UPLIFT
Austin
Houston
San Antonio
GEOSYNCLINE
SAN MARCOS ARCH

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RÉSUMÉ OF GEOLOGY OF THE SOUTH PERMIAN BASIN, TEXAS AND NEW MEXICO

West Texas Geological Society Committee: ROBERT E. KING, *Chairman*, ROBERT L. BATES, JOHN M. HILLS, B. G. MARTIN, SURCE J. TAYLOR

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ABSTRACT

In the South Permian Basin the Permian rests on an irregular surface of folded older rocks. On the east side of the basin the exposed Permian is sparsely fossiliferous. The lower part is largely limestone and the upper is red clastic sediment with layers of gypsum. In the mountains west of the Pecos River the Permian is fossiliferous limestone, sandstone, and shale except for the highest formations, which are largely gypsum and redbeds. In the subsurface the Permian strata pass through a succession of changes in lithologic facies, which are related to the regional structure. Two broad negative areas subsided during the Permian more rapidly than the

platforms bordering them. Limestone reefs and banks on the margins of the platforms grade into clastic rocks in the intervening negative areas. On the platforms, between the marginal reefs, are lagoonal dolomites, evaporites, and clastic rocks. The Permian Basin was probably connected with the open sea by way of a geosyncline crossing northern Mexico. Because of the narrowness of the entrance to the basin and the barriers to free circulation of ocean water within the basin, the salinity of the water probably varied greatly from place to place. Evaporites were deposited in areas where the salinity of the water was abnormally high.

Permian oil reservoirs are in porous dolomites, and to a lesser extent in sandstone layers. Production is obtained from several of the pre-Permian formations.

INTRODUCTION

A committee of the West Texas Geological Society prepared for the Austin meeting of the Geological Society of America, in December, 1940, an exhibit showing geological features of the South Permian Basin of West Texas and southeastern New Mexico. One part of the exhibit, a generalized cross section of the South Permian Basin, is published herein with an explanatory résumé of the stratigraphy and structure.

The cross section was compiled by Dr. Hills and Dr. Bates from information contributed by various companies and individuals operating in the region. The West Texas Geological Society is indebted to Mr. W. M. Osborn, consulting geologist, for his excellent work in drafting the cross section. The Society gratefully acknowledges the contribution by various oil companies of data obtained from well logs in their files.

The regional map (Pl. 1) was originally prepared by the West Texas Geological Society as an index map for papers presented at the mid-year meeting of the American Association of Petroleum Geologists in El Paso, Texas, in September, 1938. It has been published in several geological papers since that time. The map was brought up to date for presentation as part of the exhibit at the Austin meeting of The Geological Society of America, and it has since been further revised.

The cross section (Pl. 2) is constructed with a vertical exaggeration 10½ times the horizontal, in order to show the lithologic facies changes which are an important feature of the geology of the South Permian Basin. The principal lithologic subdivisions of the section are generalized. Because of the small scale, minor constituents of these subdivisions cannot be shown. The criteria for placing formation contacts on the cross section are in many places not obvious because the small scale does not permit showing of textural differences where rocks of the same general type occur on both sides of a contact, or the presence of thin clastic members at the base of some of the carbonate or evaporite units. Where tests drilled along the line of the section did not reach sufficient depth to show the nature of the lower formations, data obtained from deep tests

in the same structural province on either side of the line of the section are interpolated. Where insufficient subsurface control is available from deep tests, the lower portion of the section has been left blank.

Various controversial correlations and structural interpretations are shown in the cross section. An attempt will be made in this paper to state what points are controversial, and the basis for disagreement.

PHYSIOGRAPHY

The northern part of the South Permian Basin is a part of the Llano Estacado, a surface of Tertiary sand, caliche, and gravel, rising gently northwestward toward the mountains which were the source of the Tertiary beds. This surface is bounded on the west by the valley of the Pecos River. The southern boundary is formed by Cretaceous limestone mesas which characterize the Edwards Plateau. Most of the line of the cross section is in the transition zone between the Llano Estacado and the Edwards Plateau.

At the eastern end of the section most of the surface is part of the Osage Plains and has been eroded below the surface of the Llano Estacado where the two physiographic provinces meet. Successive low escarpments are formed of resistant members of the Permian section, but these are interrupted along stream divides by mesas of Cretaceous limestone. West of the Pecos River, the Permian formations rise in a succession of mountain ranges, most of which have been uplifted as a result of Tertiary block faulting. Between the ranges of Permian rocks are mountains of Tertiary volcanic rocks. The mountains bordering the Rio Grande were uplifted as a result of Tertiary orogenic movements.

STRATIGRAPHY

PRE-CAMBRIAN

In the few places where pre-Cambrian rocks have been penetrated, they differ widely in composition. Of the nine tests on the southern part of the Central Basin Platform (Pl. 1) reaching the basement, three hit gabbro or diorite (Cole, 1940), three metamorphics and three granite. On the Matador Uplift in the northern part of the South Permian Basin, one test drilled from the Mississippian into granodiorite, another from the Permian into altered rhyolite porphyry, and a third from Permian into quartzite. On the west side of the Bend flexure the basement consists of granite, gneiss, and various metasedimentary rocks. A thick section of pre-Cambrian sedimentary and volcanic rocks, and several types of plutonic igneous rocks, occur at the surface in the Llano Uplift and the Diablo Platform (Sellards, 1932, p. 30-45; P. B. King, 1940). Deep drill-

ing may eventually show that the basement rocks beneath the basin have similar diversity.

CAMBRIAN

In the Llano Uplift the pre-Cambrian is overlain by Upper Cambrian strata, about 1000 feet thick. Glauconitic sandstone at the base grades upward into alternating glauconitic sandstone and limestone, with the proportion of sandstone decreasing upward. Toward the northwest successively higher members of the Cambrian overlap upon the basement, and the basal glauconitic sandstone facies is progressively younger in that direction. In tests drilled on the Central Basin Platform the only representative of the Cambrian so far found is a cherty crystalline dolomite, about 700 feet thick, forming the lower half of the Ellenburger (Powers, 1940, p. 119; Cole 1940b), but older than the Ellenburger of the Llano Uplift, which is entirely Ordovician (Bridge and Barnes, 1941). The Cambrian portion of the Ellenburger produces oil in the southern part of the Central Basin Platform (Cole, 1940a). The lower Ellenburger overlaps monadnocks of the peneplained basement rocks. In one field more than 200 feet is missing from the base as a result of overlap (Cole, 1940a, p. 481). At the surface in trans-Pecos Texas, west of the western end of the cross section, the Cambrian appears to be completely absent (P. B. King, 1940, p. 153-156), but in the Marathon Uplift the basal formation of the Paleozoic is the Upper Cambrian Dagger Flat formation.

ORDOVICIAN

The lower Ordovician dolomite underlying the South Permian Basin forms the upper half of the Ellenburger group. Its thickness is about 700 feet. The subsurface Ellenburger probably extends higher in the Lower Ordovician time scale than the type Ellenburger in the Llano Uplift. There the Ellenburger is unconformably overlain by the Lower Mississippian, but beneath the Central Basin Platform the Ellenburger is overlain conformably by the Middle Ordovician Simpson group. In northern trans-Pecos Texas, the Lower Ordovician rocks comprise the Bliss and El Paso formations. The latter is probably equivalent to the upper half of the Ordovician portion of the subsurface Ellenburger (Bridge, 1940). In the Marathon Uplift the Marathon limestone and Alsate shale are equivalent to the Ellenburger but the Marathon limestone is of a different lithologic facies, composed of thin-bedded dense gray limestone with intraformational conglomerates (P. B. King, 1937, p. 26-30).

In the subsurface, the Ellenburger is a light-colored dolomite varying in texture from dense through finely crystalline to rhombohedral. Dolocastic chert is common in the lower part, and concretions of smooth chert

in the upper. Studies of insoluble residues have shown that different members of the group may be readily correlated by their characteristic types of cherts. The subsurface Ellenburger is practically unfossiliferous, but less dolomitic members of the El Paso limestone have a molluscan fauna, and abundant graptolites occur in the Marathon limestone.

The Lower Ordovician produces oil in one field on the Reagan Uplift, one in the Midland Basin, and five in the southern part of the Central Basin Platform. Its potentialities for future oil discoveries are believed to be great. To date most Ellenburger oil in this region has been found in highly jointed dolomite (Powers, 1940, p. 129-130) showing little porosity except in the fractures. Production is obtained from the formation where it is conformably overlain by the Simpson and also where the oil has accumulated below the eroded upper surface beneath the unconformity at the base of the Permian.

The Middle Ordovician, varying from 880 to more than 1850 feet thick where all members of it are present, rests on the Ellenburger with a sharp lithologic break but with no evidence of hiatus. The name Simpson has been applied to it from the rocks of the same age and lithology in Oklahoma. The chief lithologic subdivisions of the Simpson in the South Permian Basin resemble the formations into which the Simpson group is divided in Oklahoma (Cole, *et al.*, 1941, p. 1057).

In the South Permian Basin the different members of the Simpson group are very persistent laterally but variable in thickness. There are three main limestone members, at the base, middle, and top of the group. Between the limestones are green shales with thin layers of sandstone and limestone. An important characteristic is the presence of scattered round frosted sand grains, which occur both in the sandstones and in clusters and isolated scattered grains in the shale and limestone. Black phosphatic grains are common in the sandstones. The shales contain graptolites, and ostracodes and orthid and strophomenid brachiopods are abundant in the limestones.

The Simpson of the South Permian Basin and that of Oklahoma were certainly connected through the Llanoria geosyncline. No connecting link between the two areas across the foreland has yet been found by drilling, as the Simpson has not been encountered between the Central Basin Platform and southern Midland Basin on the southwest and the Electra Arch on the northeast. However, there is a remarkable uniformity in the lithologic subdivisions and faunas between Oklahoma and West Texas. As the faunas probably could not have migrated through the geosyncline from one foreland area to the other, some connection, as yet undiscovered, must have existed. Remnants of foreland

Simpson in structurally low areas south of the Electra Arch may have been deposited in such a connecting basin.

Oil and gas are produced from three different sandstones in the Simpson in three oil fields in the southern part of the Central Basin Platform.

The Upper Ordovician (Richmond) has been identified in several deep tests in the Central Basin Platform. It is a cherty limestone about 250 feet thick, which resembles the Montoya formation of northern trans-Pecos Texas.

SILURIAN

A coarsely crystalline, somewhat glauconitic limestone 180 to 200 feet thick, occurring on the Central Basin Platform, is believed to be correlative with the Middle Silurian Fusselman formation of northern trans-Pecos Texas (Cordry and Upson, 1941). The limestone is overlain by green, gray, and black shale interbedded with dense limestone. This unit is 180 feet thick on the west side of the Central Basin Platform but wedges out eastward. The shale is placed in the Devonian on Plate 2, but since the preparation of the plate the green shale has been found to contain a Middle Silurian graptolite (C. D. Cordry, personal communication, December, 1941). The black shale contains resinous spores. The Silurian limestone produces oil in one field in the southern Central Basin Platform (Cordry and Upson, 1941).

DEVONIAN

A section of interbedded calcareous chert and siliceous limestone, with a maximum thickness of 986 feet, occurs between the Silurian and the Pennsylvanian in the Central Basin Platform. Northward from the line of the cross section the chert and limestone grade into siliceous spore-bearing shale.

The siliceous section is generally regarded as Upper Devonian and believed to be the partial equivalent of the Caballos chert and novaculite of the Marathon Uplift (Cordry and Upson, 1941). Brachiopods, trilobites, bryozoans, and ostracodes which occur in the upper part of the formation are reported to indicate Devonian or Silurian age. Some geologists question the fossil evidence, and suggest that these beds are Lower Mississippian because they resemble some of the more cherty portions of the Chappel limestone of central Texas. Baker (1940) reports that novaculite resembling the Caballos occurs in the Lower Mississippian Lake Valley limestone in the San Andres Mountains of southern New Mexico. The siliceous shale of the northern facies of the supposed Devonian of the subsurface resembles the Chattanooga and Woodford shales, of lowest Mississippian age, in the Mid-Continent region. Black spore-bearing shale which occurred directly beneath the Permian in a test north of the

line of the cross section in western Andrews County, Texas, has been assigned to the Lower Mississippian (Fritz and FitzGerald, 1940, p. 21).

MISSISSIPPIAN

Mississippian formations occur in the Llano Uplift, on the Bend flexure, and along the eastern edge of the South Permian Basin. They are not definitely known from the Central Basin Platform, unless the supposed Devonian formation, and the lower part (Bend) of the Pennsylvanian, prove to be Mississippian. Limestone and shale with a Chester fauna, the Helms formation, occur at the surface in northern trans-Pecos Texas, and Lower Mississippian limestone, the Lake Valley formation, crops out in the Sacramento and San Andres Mountains of New Mexico.

The Lower Mississippian Chappel formation is exposed in the Llano Uplift as a coarsely crystalline, crinoidal limestone which overlaps the irregular surface of the Ellenburger. The formation is absent in places and as much as 150 feet thick elsewhere. Locally in the subsurface it reaches a thickness of 300 feet, and an unusually cherty portion of the formation wedges in. The cherty member appears to be absent at the surface (Cheney, 1940, p. 67). The Chappel produces oil in several fields in north central Texas.

The Upper Mississippian Barnett formation is a brown and black shale varying in thickness from 30 to 50 feet at the surface in the Llano Uplift to 200 feet or more in the subsurface in north central Texas (Sellards, 1932, p. 92-94). The Barnett probably continues northward in the subsurface to connect with the lower part of the Caney shale of Oklahoma.

PENNSYLVANIAN

The well-known Pennsylvanian section of north central Texas (Sellards, 1932, p. 98-127; Cheney, 1940) thins gradually westward into the South Permian Basin, and coarse clastic members of the section grade into shales and limestones. The lowest Pennsylvanian series, the Bend, wedges out completely on the eastern edge of the South Permian Basin. The Strawn, the most coarsely clastic part of the Pennsylvanian on the east flank of the Bend flexure, grades westward to shale and crinoidal limestone. The Canyon series, which is alternating shale and limestone on the Bend flexure, grades into a limestone reef in the vicinity of Abilene, in Taylor County, thence westward into a clastic facies which extends beneath the Midland Basin. At the surface the Cisco series consists of shale with interbedded limestone and sandstone. Westward, the limestone decreases, and beneath the Midland Basin the Cisco is predominantly shale. The Pennsylvanian-Permian contact is difficult to place in the Midland Basin and beneath the Eastern Platform, be-

cause both the Cisco and the Wolfcamp are predominantly dark shale with a few thin fossiliferous limestones. In parts of the Midland Basin the basal Permian directly overlies limestone of Strawn age, which in turn rests on the Simpson.

The Pennsylvanian has been found in a few deep tests drilled in the Central Basin Platform. It ranges from 1650 to 2700 feet thick, but the complete thickness originally deposited is unknown because of the profound unconformity at the base of the Permian. In this area the Pennsylvanian is separated lithologically into two chief parts. The lower is shale of probable Bend age and the upper is limestone, gray shale, and conglomeratic red shale, which are equivalents of the Strawn, Canyon, and Cisco. The lower shale is present along the line of the cross section. In a deep test west of the Yates field it is absent, and the only possible representative of the Bend is a limestone 42 feet thick (Carsey, 1936). It is possible that the lower shale is actually of Chester age, and equivalent to the Barnett.

An important erosional unconformity and a minor tectonic discordance separate the Pennsylvanian from older systems. On the Central Basin Platform the Pennsylvanian overlies the Simpson west of the Yates field, and it rests on the Devonian where encountered in Gulf, McElroy No. 103, in the McElroy field.

In two tests in the Delaware Basin that have drilled into the Pennsylvanian the section is dark shale and limestone (Dunbar and Skinner, 1937, p. 592). In northern trans-Pecos Texas and southern New Mexico the Pennsylvanian is largely limestone. The portion of this section with a Bend-Atoka fusulinid fauna is thick and widespread in this region. In the Marathon Uplift the Pennsylvanian is as much as 12,000 feet thick. It is largely clastic except for the Dimple limestone, which is equivalent to at least part of the Bend.

The Pennsylvanian produces oil in numerous fields from the vicinity of Abilene eastward, but in the South Permian Basin two fields on the Reagan Uplift (Christner, 1940; Cole, *et al.*, 1941, p. 1055) and one on the Eastern Platform (Simpson, 1941), producing from limestone of Strawn age, are the only ones that have yielded Pennsylvanian oil and gas in commercial quantities. Favorable showings of oil were encountered in Pennsylvanian limestones in Gulf, McElroy No. 103 and in Moore, McDowell No. 1 (Pl. 2).

PERMIAN

General features.—The lithologic and faunal facies of the Permian strata on the eastern and western sides of the South Permian Basin have little in common. On the east side of the basin the lower part

of the Permian is alternating limestone, sandstone, and red shale, overlain by limestone and shale of the "Wichita" group. The succeeding Permian formations are largely red clastic rocks and gypsum. Except in the lowest part of the Permian, fossils are rare. The different stratigraphic units can be traced for long distances. They show regional transitions, such as gradual change in the proportion of limestones and clastic rocks, and gradation from red to gray and green shale and sandstone.

In the mountains west of the Pecos River the Permian strata are fossiliferous marine rocks, except for the highest beds, where gypsum and redbeds occur. Where the Permian limestones are dolomitic, fossils are obscure, but abundant molds show that fossils were originally common. Abrupt changes in lithologic and faunal facies cause sections in mountain ranges a few miles apart to be quite dissimilar.

During the last 15 years the correlation of general units between opposite sides of the basin has been made possible by detailed study of the stratigraphy and paleontology of the outcrop sections on both sides of the South Permian Basin by many geologists, and by study of the cuttings from thousands of wells.

The Permian sea of the basin probably connected through the Delaware and Marfa basins to a geosyncline crossing northern Mexico to connect with the open ocean. Because of the narrow entrance to the Permian Basin during most of Permian time, and the platform barriers to free circulation of sea water, the ocean currents were unable to contribute a supply of water of normal salinity to all parts of the basin. Rivers entering from the land lowered the salinity in certain areas, and excess evaporation increased it in others (Baker, 1929). The only parts of the Permian Basin in which marine fossils are abundant and varied throughout most of the Permian are in the Delaware and Marfa basins and their borders. The salinity of the sea water here probably closely approached that of the open sea. The faunas are closely allied to those of the Permian which was deposited in the Tethyan geosyncline of Europe and Asia, and correlation of some of the larger units with corresponding units of other continents are more satisfactory than some correlations from the Delaware Basin into the sparsely fossiliferous platform facies.

The Permian was deposited on an irregular surface of the older rocks, formed as a result of late Pennsylvanian folding. Two broad negative areas, the Delaware and Midland basins, subsided progressively during the Permian at a more rapid rate than the platforms bordering the basins. The shallow sea floor of the platforms probably was more than 1000 feet above the bottom of the sea in the deepest part of the

basins. On the margins of the platforms limestone reefs and banks developed (P. B. King, 1934, p. 788-790). The reefs grade basinward into clastic rocks, and away from the basins into lagoonal dolomites, evaporites, and clastic beds.

Because of periodic slowing of the rate of subsidence of the sea floor, and perhaps to withdrawals of the sea from all but the deepest basins, sedimentation continued in the basins while little or no deposition took place on the platforms. Consequently, the section in the basins contains members deposited at times of hiatus in the geologic record of the platforms.

The Permian is divided into four series (Adams, *et al.*, 1939), the type localities of which are in the Delaware Basin and its bordering mountain ranges.

Wolfcamp series.—In the South Permian Basin a highly variable thickness of Wolfcamp strata rests on an uneven surface of the Pennsylvanian and older rocks. The Wolfcamp is entirely missing from some of the topographically higher parts of the pre-Permian surface in the Central Basin Platform, and the series has its maximum development in the Midland Basin and possibly in the Delaware Basin. On the Central Basin and Diablo platforms the Wolfcamp is largely limestone, with a variable thickness, up to 438 feet (Cole, *et al.*, 1941, p. 1061), of red and green shale and conglomerate at the base. Beneath the Delaware and Midland basins and the Eastern Platform the Wolfcamp is dark shale and brown sandstone. On the west flank of the Bend flexure the exposed Wolfcamp contains thin alternations of red and gray shale, sandstone, and limestone (Cheney, 1940, p. 94-97). Here the unconformity at the base of the Permian is of small magnitude; therefore, the lowest Wolfcamp beds are probably older than those in the Central Basin Platform. In the eastern facies, the formations and members of the Wolfcamp are persistent laterally. Oil is produced from the Wolfcamp in several fields northwest of Abilene.

A marked faunal change occurs between the Cisco and the Wolfcamp. New invertebrate forms which appear at the base of the Wolfcamp are precursors of the fossils characterizing the Permian. The Wolfcamp is the faunal zone of the fusulinids *Schwagerina* and *Pseudoschwagerina,* the gastropod *Omphalotrochus,* and the ammonoid *Properrinites. Schwagerina* extends from the base of the Wolfcamp into the overlying Leonard, but *Pseudoschwagerina* is restricted to the Wolfcamp. The chief guide fossil in its flora is the genus *Callipteris.* The Wolfcamp is equivalent to the Sakmarian of Russia, which many Russian geologists place in the Upper Carboniferous, but others believe to be Permian.

Leonard series.—In the Delaware Basin the Leonard series is represented by the Bone Spring formation, which is a black calcareous shale interbedded with black limestone. Near the margins of the Delaware Basin the upper part of the Bone Spring grades into the Victorio Peak limestone reef facies. North and east of the periphery of the Delaware Basin, the correlation of the top of the Leonard is controversial. The San Andres group, the age of which is questionable, will be discussed in a separate section. In the southern Midland Basin the unquestioned Leonard of the "Wichita" and Clear Fork groups is black and dark-gray shale with thin limestone and dolomite layers and fine-grained sandstone. Northward the proportion of limestone increases, and it predominates in the upper part. In the Central Basin Platform the "Wichita" and Clear Fork groups are dolomite with a minor amount of limestone. Several very cherty zones in the Leonard are excellent markers for correlation. Under the Eastern Platform the "Wichita" and Clear Fork shale and limestone of the Midland Basin grade to a thick mass of cherty dolomite. Farther east, shales grade into this dolomite, increasing in proportion eastward, and the dolomite of the lower part of the section changes to limestone. At the east end of the cross section the "Wichita" is limestone with some shale and one important anhydrite layer. It grades northward toward the Red River into a red clastic facies. The Clear Fork is red shale and sandstone with several beds of limestone and dolomite. The name "Wichita" is used here in the sense proposed by Dickey (1940, p. 42) for the beds between the top of the Wolfcamp and the base of the Clear Fork. Prior usages of the name Wichita were for beds from the Camp Colorado or Coleman Junction members of the Wolfcamp to the base of the Clear Fork.

In the Glass Mountains and Sierra Diablo there is a marked unconformity at the base of the Leonard, but this break appears to be of minor importance elsewhere in the South Permian Basin.

The Leonard series is most fossiliferous in the Sierra Diablo and in the type area of the series in the Glass Mountains. The lithologic facies in both these ranges are transitional from the Delaware Basin clastic rocks to the dolomite and limestone of the bordering platforms. The more important guide fossils are the ammonoid *Perrinites hilli*, the brachiopod *Dictyoclostus bassi* (*Productus ivesi* of authors), and several species of *Parafusulina* that are less advanced than those in the succeeding series. *Parafusulina* does not extend to the base of the Leonard. Several species of *Schwagerina* characterize the beds of the series below the lowest which contain *Parafusulina*. Aberrant genera of brachiopods that are especially characteristic of Permian faunas are common in the

Leonard. On the east side of the South Permian Basin the Leonard contains a flora of which *Gigantopteris* is the principal guide fossil.

The pays of several producing oil fields in the southern part of the Central Basin Platform and a deep pay in the Wasson field are of unquestioned Leonard age. Several of the fields on the Eastern Platform produce from pays in the Clear Fork.

San Andres group.—The San Andres is here regarded as a group because it is divisible into several formations in different parts of the South Permian Basin. The type locality of the San Andres is in the San Andres Mountains of New Mexico, where it is a limestone 500 feet thick (Lee and Girty, 1909, p. 29). The name has been applied in the subsurface to a succession of dolomite beds with subordinate limestone members, which reaches a thickness as great as 1460 feet (Dickey, 1940, p. 43). The San Andres cannot be traced continuously from its exposures at the type locality into the subsurface. However, there is little doubt that the San Andres is correctly identified in the Sacramento Mountains (Lang, 1937, p. 852-855), and from its exposures there it is traceable into at least the lower part of the subsurface unit. The San Andres has not been followed with certainty from the Sacramento Mountains southeastward into the Delaware Basin section. Some geologists believe that the San Andres traces into the Victorio Peak facies of the upper Bone Spring, and others that it extends southward into a reef facies of the middle one-third of the Guadalupe series (Lewis, 1941, p. 92-96). Still other geologists contend that the type San Andres is equivalent to the Victorio Peak and that the upper part of the subsurface San Andres is younger than the typical San Andres, being equivalent to the middle third of the Guadalupe (Dickey, 1940, p. 43-44).

The dolomite facies of the San Andres extends northward from the Delaware Basin to the latitude of Roswell, where anhydrite members appear in the section. Farther north the greater part of the upper San Andres grades to salt and anhydrite. East of the Delaware Basin, on the Central Basin Platform, the San Andres dolomite contains an upper, light-colored, noncherty portion and a lower, dark, cherty portion. Cox and Winter (1940) have proposed the name "Goldsmith formation" for the upper portion and suggest restricting the name San Andres to the lower, as they believe that only the lower portion is equivalent to the type San Andres and that it is separated from the "Goldsmith" by an unconformity. Some other geologists believe, however, that the contact between the two lithologic subdivisions is gradational and hence not everywhere of the same age.

The accompanying cross section (Pl. 2) shows a reef facies of the San Andres along the margins of the Delaware and Midland basins. The reef is indicated as grading basinward to clastic rocks. If the same correlation is applied to the southern part of the Midland Basin, south of the line of the cross section, the lower San Andres is shale and the upper is dolomite and limestone (Lewis, 1941, p. 86-88). The contact between the lower shale and upper limestone varies in age from place to place. According to another interpretation, the beds in the Midland Basin here placed in the San Andres are younger, and near the axis of the Central Basin Platform and east of the Midland Basin they overlap against reefs of true San Andres age. The top of the San Andres of the Central Basin and Eastern platforms in Plate 2 would then be correlated with the horizon shown as the top of the Clear Fork in the Midland Basin.

The reef facies of the San Andres on the Eastern Platform grades eastward to dolomite and limestone, then to red and green shale with thin layers of dolomite and anhydrite. The lower part of the San Andres here is the San Angelo sandstone and conglomerate, which becomes coarser and thicker southeastward toward San Angelo. The upper members of the San Andres are progressively truncated to the east by an unconformity at the base of the overlying Whitehorse group.

Much evidence has been advanced on both sides of the controversy as to whether the San Andres is of Leonard or Guadalupe age, or both. On the platforms and on the eastern side of the South Permian Basin an important unconformity occurs at the top of the San Andres. The only unconformity of comparable magnitude in the Permian of the Delaware Basin is that between the Leonard and Guadalupe series, which may be studied at the surface on the northwestern side of the basin in the Guadalupe Mountains. The fauna of the type San Andres of the San Andres Mountains is closely related to that of the Leonard series. *Perrinites*, regarded as the guide ammonoid genus of the Leonard, occurs at the surface in San Andres beds on the east side of the South Permian Basin. On the other hand, fusulinids conspecific with Guadalupe forms are reported from the San Andres in the Central Basin Platform and Midland Basin (Lewis, 1941, p. 99-100). Evidence from brachiopods in the subsurface San Andres appears to be inconclusive (Stainbrook and Madera, 1941). According to some geologists, subsurface correlations indicate connection of at least the upper San Andres of the subsurface in the region peripheral to the Delaware Basin with the Guadalupe beds of the Glass and Guadalupe mountains (Lewis, 1941, p. 90-96). Rocks of middle Guadalupe age in the Glass Mountains (Word formation) are very cherty. This suggests correlation with at least part of the subsurface San Andres, as chert is very rare in the overlying White-

horse group. Some geologists believe the lower part of the San Andres subsurface is Leonard and the upper part Guadalupe. The upper part could be entirely younger than the type San Andres. The Leonard fauna of the type San Andres and of the outcrop on the east side of the South Permian Basin might occur in the lower part of the San Andres, and the Guadalupe fusulinids reported from the San Andres in the Central Basin Platform could be from the upper part, which is probably absent from the eastern and western outcrops as a result of erosion or nondeposition. However, Guadalupe fusulinids are reported to occur in the lower part of the San Andres in the Midland Basin (Mohr, 1939, p. 1698).

The San Andres contains the oil and gas pays of the Vacuum, Hobbs, Wasson, and Slaughter fields, some of the important oil fields in the eastern part of the Central Basin Platform, including at least part of the pay of the Yates field, some of the oil fields in the Midland Basin, and the most important pays of fields on the Eastern Platform.

Guadalupe series.—In the Delaware Basin the Guadalupe series comprises the Delaware Mountain group, which is divided from base to top into the Brushy Canyon, Cherry Canyon, and Bell Canyon formations. The Delaware Mountain is a fine-grained sandstone with thin layers of black shale and argillaceous limestone. A persistent bentonite zone occurs near the top of the Cherry Canyon. Toward the margins of the Delaware Basin the limestones and shales of the upper two formations thicken and in this facies are much more fossiliferous than the limestones in the deeper part of the basin. At the surface on the western face of the Guadalupe Mountains, the Brushy Canyon wedges out entirely against a monoclinal flexure in the Bone Spring, and it is commonly believed that, as shown in the cross section, this may occur generally at the margin of the basin. At the surface, there is a conglomerate at the base of the Brushy Canyon where it overlaps the Bone Spring. In the Guadalupe and Glass mountains the Cherry Canyon and its equivalents grade into a reef limestone on the edge of the platform. The Bell Canyon likewise grades into a reef limestone, the Capitan, but this extends farther basinward than the reef of Cherry Canyon age. Due to basinward growth, the higher part of the reef reaches farther into the basin than the lower part.

Beyond the limits of the Delaware Basin, the beds from the top of the San Andres to the top of the Guadalupe series are known as the Whitehorse group. In a direction normal to the margin of the Delaware Basin, the Whitehorse grades from gray coarsely crystalline reef limestone and dolomite into buff to tan, well-bedded dolomite interbedded

with fine-grained sandstone, thence to alternating anhydrite, dolomite, and sandstone. In the eastern part of the Central Basin Platform, and north of the platform, the Whitehorse contains alternations of red sandstone, anhydrite, salt, and dolomite, with the dolomite predominating in the lower part. This facies persists eastward across the Midland Basin and Eastern Platform, but toward the outcrop on the east side of the South Permian Basin the evaporites thin, and the outcrop section is predominantly red clastic rock.

The Whitehorse group, as the term is used in the South Permian Basin, is divided into five formations, the Grayburg, Queen, Seven Rivers, Yates, and Tansill. These are particularly useful as subsurface units, but they are also mappable surface units in the mountains west of Carlsbad, New Mexico, where they are well exposed. The formations of the Whitehorse have been defined by Dickey (1940, p. 44-49), Page and Adams (1940, p. 59-61, Fig. 2) and DeFord and Riggs (1941). The Queen and Yates sandstones are particularly characterized by abundant rounded, frosted grains of quartz sand, about 0.6 mm. in diameter, which are scattered irregularly through poorly sorted silts and fine sands that are generally red. The frosted sand grains are useful as an aid to subsurface correlations, as they can be found in many suites of contaminated rotary cuttings in which other diagnostic lithologic markers cannot be recognized.

On the platforms, the Whitehorse is unconformable upon the San Andres. Presumably, deposition proceeded with less interruption in the basins, and in these areas the break is probably of less magnitude. From the Eastern Platform eastward to the outcrop the unconformity at the base of the Whitehorse increases, and the Whitehorse truncates the eroded surface of the San Andres. The correlation of the Whitehorse formations eastward from the Midland Basin is controversial. The sandstone on the Eastern Platform which is shown as Queen on the cross section is believed by many geologists to be the Yates. The latter interpretation would necessitate a change in the correlations on the cross section between Phillips, Stokes No. 1 and Moore, McDowell No. 1.

The lower two formations of the Guadalupe series in the Delaware Basin and its bordering reefs contain a fauna characterized by the ammonoid *Waagenoceras* and by more advanced forms of the fusuline genus *Parafusulina* than those in the Leonard. In the Bell Canyon formation, *Waagenoceras* is present, but the more advanced genus *Timorites* appears. *Parafusulina* is replaced here by *Polydiexodina*. The other elements in the fauna show little relationship to the Pennsylvanian, though some forms in the Leonard series have Pennsylvanian affinities. The Whitehorse fauna is restricted, and at scattered localities contains principally pelecypods and gastropods (Newell, 1940).

The alga *Mizzia*, common in the Permian of Asia and Europe, is locally common in upper Guadalupe limestones (Johnson and Dorr, 1942).

The Guadalupe section above the San Andres contains the oil pays of Hendrick and other fields along the western margin of the Central Basin Platform, the North Cowden and several other fields on the eastern side of the platform, and some of the lesser pays of the Eastern Platform fields. The Bell Canyon sandstone produces oil and gas in five fields in the Delaware Basin.

Ochoa series.—The lowest formation of the Ochoa series, the Castile anhydrite and salt, is restricted to the Delaware Basin (Kroenlein, 1939; Lang, 1939). It probably was deposited at a time when the South Permian Basin as a whole was quiescent, and the floor of the Delaware Basin was much lower than the surface of the surrounding platforms as a result of movement during Guadalupe time. A barrier south of the Delaware Basin may have prevented the open sea from reaching the restricted area of the basin, as a result of which carbonates were excluded from the basin. In the southern and western parts of the Delaware Basin the Castile grades into alternating anhydrite and dolomite, and in the Glass Mountains the Tessey reef dolomite overlying the back-reef Guadalupian dolomite and sandstone is probably in part equivalent to the Castile.

The Salado salt and anhydrite (Kroenlein, 1939; Lang, 1939) extends from the Delaware Basin across the bordering platforms and occurs throughout the Midland Basin north of a line between San Angelo and the Yates field. The formation wedges out 50 miles north of a line from Lubbock to Roswell. However, equivalents of it may occur as far north as the Anadarko Basin, if one possible correlation between West Texas and western Oklahoma is correct. In the eastern part of the Midland Basin red clastic wedges appear in the Salado in places, and in certain areas almost the entire formation grades to red shale and siltstone near its easternmost occurrence. In many parts of the South Permian Basin beyond the limits of the Delaware Basin a red shale layer occurs at the base of the Salado directly above the unconformity. The commercial potash deposits near Carlsbad, New Mexico, are in the Salado formation.

In the western part of the Delaware Basin the Rustler formation is a dolomite with subordinate layers of anhydrite. It grades eastward to anhydrite, redbeds, and some salt, which form a persistent stratigraphic unit above the Salado salt and below the younger redbeds. By some geologists, the Rustler is correlated with the Alibates dolomite, which occurs near the top of the Permian in the Amarillo Uplift; others

place the Alibates in the Guadalupe. In places a marked unconformity occurs at the base of the Rustler.

The Dewey Lake red sandstone and siltstone overlies the Rustler conformably (Page and Adams, 1940, p. 62-63). Scattered subangular and rounded grains of frosted quartz sand are common in the lower 10 feet of the formation and occur also in higher parts.

The Ochoa series is practically unfossiliferous. The fossils which occur are generally unidentifiable.

The Ochoa is not an important oil reservoir, but oil occurs in places in it as well as in the Triassic and Quaternary, probably as a result of seepage upward along fractures.

Nature of Permian oil and gas reservoirs.—In the South Permian Basin oil reservoirs occur on anticlines and monoclinal flexures with subordinate anticlinal closures on the major structure. Some of the anticlines are plunging folds on regional homoclines, but these may originally have been closed structures before regional tilting took place. The oil pays are not uniformly distributed over most of the anticlines, but instead are best developed on one flank, generally that facing the deep basin, where the greatest porosity commonly is present.

In the Whitehorse group the oil-bearing rocks are generally sandy. Some are sandstones interbedded with dolomite or evaporites. In them, oil accumulation is controlled by local variations in porosity and permeability of the sandstones and by the wedging-out of the sandstones between impervious strata. Many such fields occur along the lagoonal border of the Capitan reef. Other Whitehorse pays are in dolomite interbedded with calcareous sandstones and sandy dolomites. In such pays the porosity commonly occurs only in the dolomite. These conditions prevail in various fields producing from the Grayburg formation on the eastern side of the Central Basin Platform and from the Seven Rivers, Yates, and Tansill in the Capitan reef zone on the west side of the platform.

In the San Andres and lower formations the oil reservoirs are in nonsandy porous dolomite, and rarely in limestone.

There is no general agreement as to the origin of porosity in the Permian dolomites. Some geologists believe that all porous zones closely underlie unconformities. In certain fields such as Yates, Hobbs, and Vacuum, the porosity occurs directly below the unconformity at the base of the Whitehorse, and in these fields the porosity is exceptionally high. In other fields, including Hendrick, Wasson, and Monument, many geologists doubt the existence of unconformities directly above the pays. In Monument the stratigraphic range of the pay section is 650 feet, and

the upper limits of the porosity vary from one part of the field to another, being limited upward by the presence of anhydrite which grades laterally into the Whitehorse dolomite toward the southwest. This zone of porosity can hardly be related to an unconformity. However, some of the porous zones appear to occur at a certain definite stratigraphic position in different parts of the basin.

Certain general characteristics of the porous zones in Permian dolomites may be noted. The porosity in some fields is in intercrystalline spaces and small pits. In others there are interconnecting vesicles in granular dolomite, molds of dolomitized fossils such as fusulinids, and irregular large cavities. Porosity is generally greatest near the steep flanks of monoclines and asymmetrical anticlines, that is, on the edges of the platforms and local uplifts in the platforms. This may be due to enlargement of voids within growths of organisms, such as calcareous algae, which contributed to the formation of limestone reefs on the edges of the basins, and also due to the downwarping of the strata after deposition, to place them in contact with the cool waters below the surface of the basins. Lateral decrease in porosity in a field is generally accompanied by primary anhydrite which wedges into the porous zone, and by secondary anhydrite which has been deposited in pore spaces. The original porosity in the pays is generally enlarged in wells by acid treatment or shooting with nitroglycerin (Young, *et al.*, 1939, p. 1544-1545).

Porous zones in Permian dolomites are commonly cherty, and many of them contain bentonite, either as distinct layers or disseminated in small quantities throughout. Some of the chert has the appearance of silicified bentonite. Possibly climatic conditions during times of volcanic activity in northern Mexico (R. E. King, 1934) and the western United States (Wheeler, 1940) were related to the development of some zones of porosity in the South Permian Basin.

TRIASSIC

Upper Triassic red shales and sandstones of terrestrial origin overlie the Permian throughout much of the South Permian Basin. They are placed in the Dockum group, and are divided in ascending order into the Tecovas shale, Santa Rosa sandstone, and Chinle shale. In places the Tecovas is absent, and the Santa Rosa overlaps upon the Permian (Sellards, 1934, p. 392-393; Page and Adams, 1940, p. 63-64).

CRETACEOUS

The Cretaceous overlaps the South Permian Basin from deep basins of deposition to the south and east. On the borders of the Marathon

Uplift the Glen Rose overlies the Paleozoic. From the Glass Mountains to the vicinity of Midland the Paluxy sandstone, and from there successively younger members of the Fredericksburg group appear to overlap the older rocks.

STRUCTURE

The regional tectonic features of the South Permian Basin are shown in Plate 1. The arc of the Marathon-Ouachita folded belt, formed in Pennsylvanian time from the sediments deposited in the Llanoria geosyncline, borders the Permian Basin on the south. Uplifts and basins in the foreland radiate from the two salients of the folded belt. From the Marathon salient in West Texas the Diablo and Central Basin platforms and the Delaware Basin extend normal to the periphery of the Pennsylvanian folds. From the Ouachita salient in southeastern Oklahoma extend the Arbuckle Mountains and the Red River uplifts.

Deep drilling has shown that the pre-Permian rocks beneath the Central Basin Platform are strongly folded and suggests that they may be considerably faulted, though as yet there is definite proof of faulting in only one area, where both normal and thrust faults have been intersected in wells. The fault shown in the cross section is assumed to exist, but has not been cut by a well. Dips as high as 75° have been found in cores of the Ordovician. The pre-Permian rocks evidently are uplifted to a high median axis in the Central Basin Platform, and subsidiary folds apparently occur on the flanks. Toward the north the Ordovician, Silurian, and Devonian beds wedge out on the south flank of an axis where the Permian and Pennsylvanian rest on the pre-Cambrian. This feature, here called the Matador Uplift (Pl. 1), is a western extension of the Electra Arch.

In the Permian, positive axes grew progressively, so that dips become accentuated with depth. This movement may have been the consequence of compaction of sediments deposited on the flanks, and of isostatic adjustment which followed the folding and erosion of the pre-Permian rocks in a relatively brief time in the late Pennsylvanian. Permian axes follow a characteristic en échelon pattern, probably related to folds in the older rocks. However, the axes of Permian and pre-Permian folds rarely coincide (Sellards, 1934, p. 125-128), and the axes of many folds even shifted progressively throughout the Permian. The steepest dips in the Permian are on the margins of the Delaware Basin, San Simon Syncline, and Sheffield Channel (Pl. 1). On the border of the Delaware Basin they are as great as 25° but elsewhere dips as high as 10° are very exceptional. Some of the steeper dips may be only original

depositional dips on the margins of limestone reefs or banks, slightly modified by later movements.

The structure of the Permian rocks has not been greatly modified by post-Permian deformation except in the mountains of the trans-Pecos region, where they are locally involved in the Tertiary folds and more generally cut by Tertiary normal faults and some intrusions. Several intrusions of basic igneous rock have been encountered in drilling in the Delaware Basin. Except for superficial faults due to collapse of beds following solution of Permian salt, the existence of faults cutting the Permian rocks of the subsurface is questionable, though some may occur in the Delaware Basin. The cross section (Pl. 2) shows a zone of slump on the western edge of the Central Basin Platform, which may be the result of salt solution along a fault line at the western edge of the platform. Similar slump in the valley of the Pecos River is probably due to salt solution by meteoric waters rather than to any deep-seated cause.

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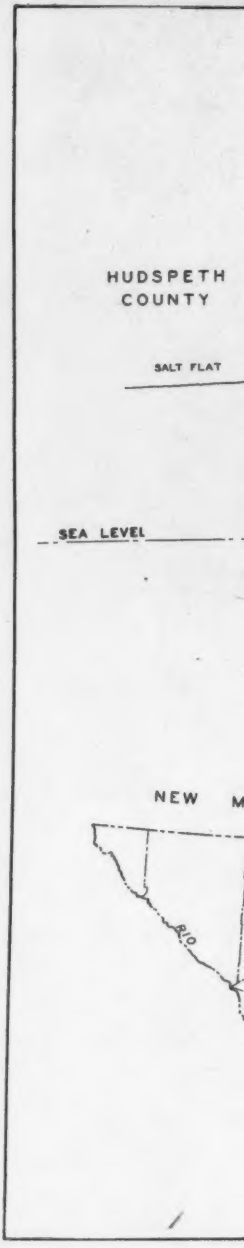
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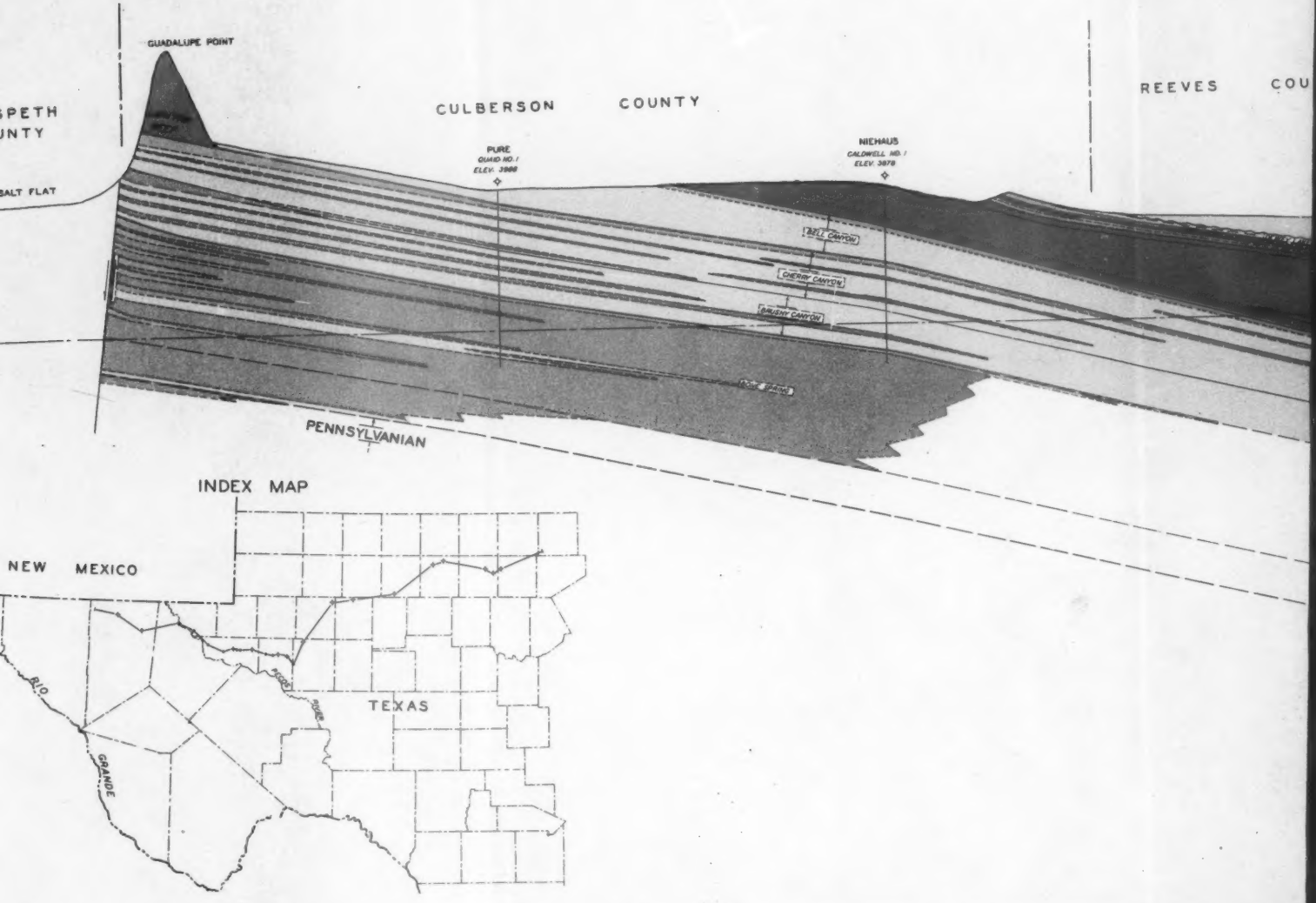
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ELEV. 3878
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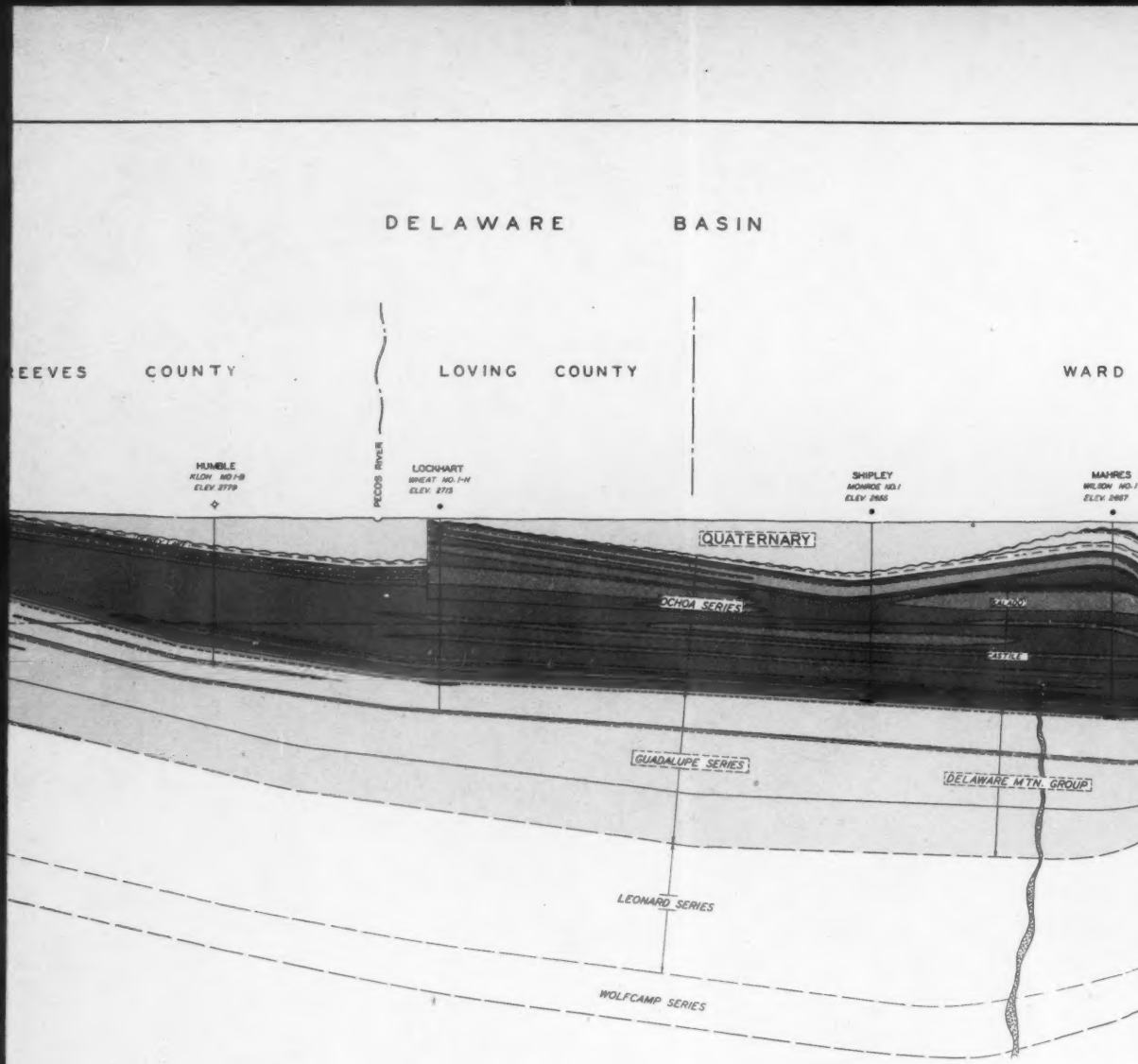
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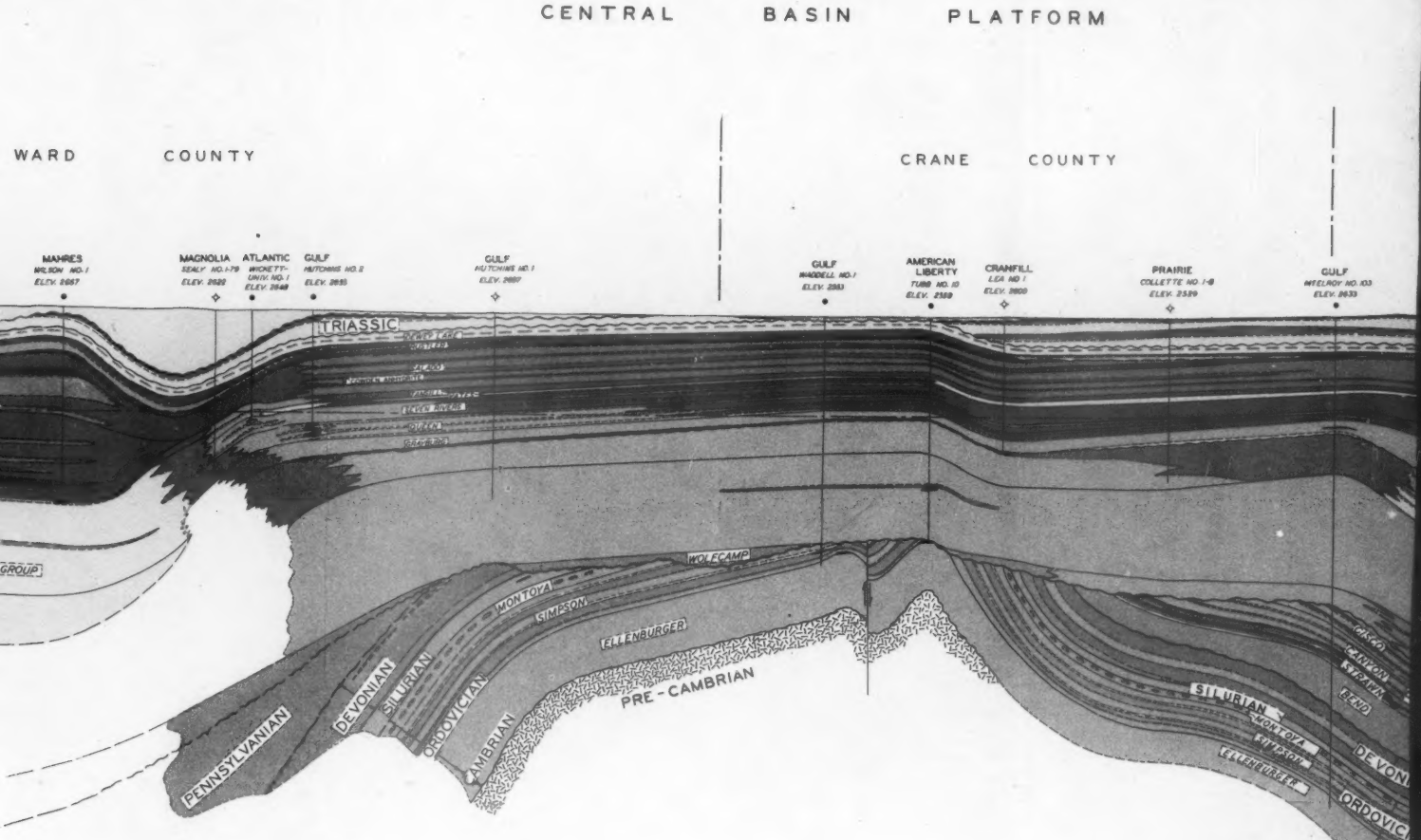

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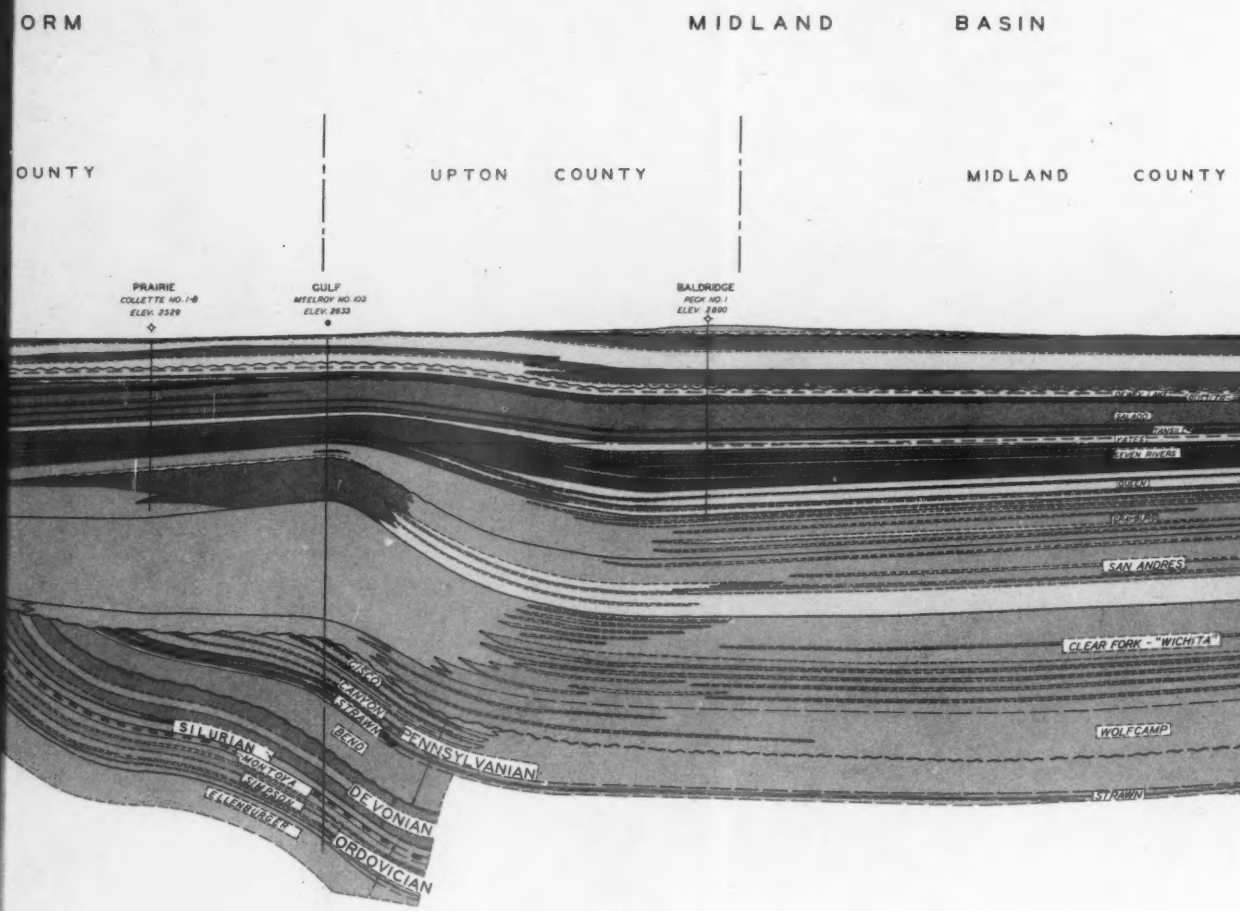

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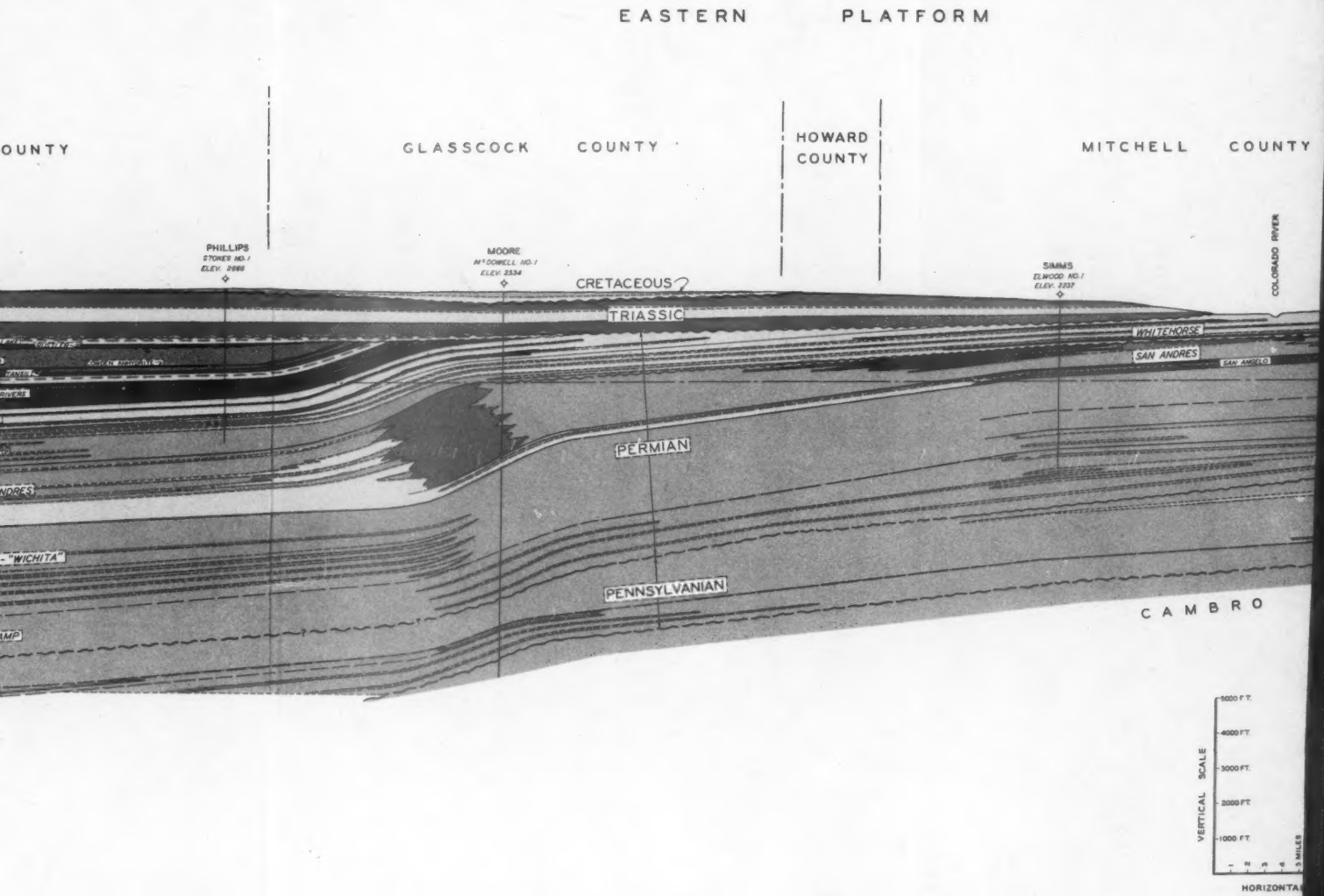
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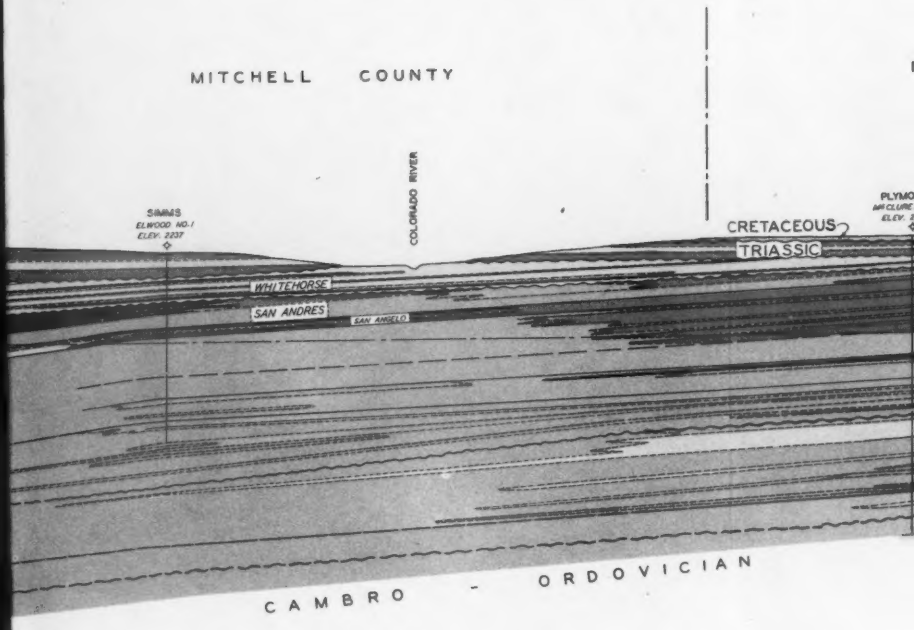
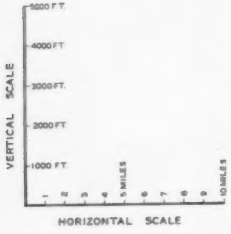
ELEV. 2688
MOORE
McDOWELL NO. 1
ELEV. 2534
SIMMS
ELWOOD NO. 1
ELEV. 2237
COLORADO RIVER
CRETACEOUS?
TRIASSIC
WHITEHORSE
SAN ANDRES
SAN ANGELO
PERMIAN
"WICHITA"
PENNSYLVANIAN
CAMBRO
VERTICAL SCALE
5000 FT.
4000 FT.
3000 FT.
2000 FT.
1000 FT.
HORIZONTAL

AN BASIN

FORM





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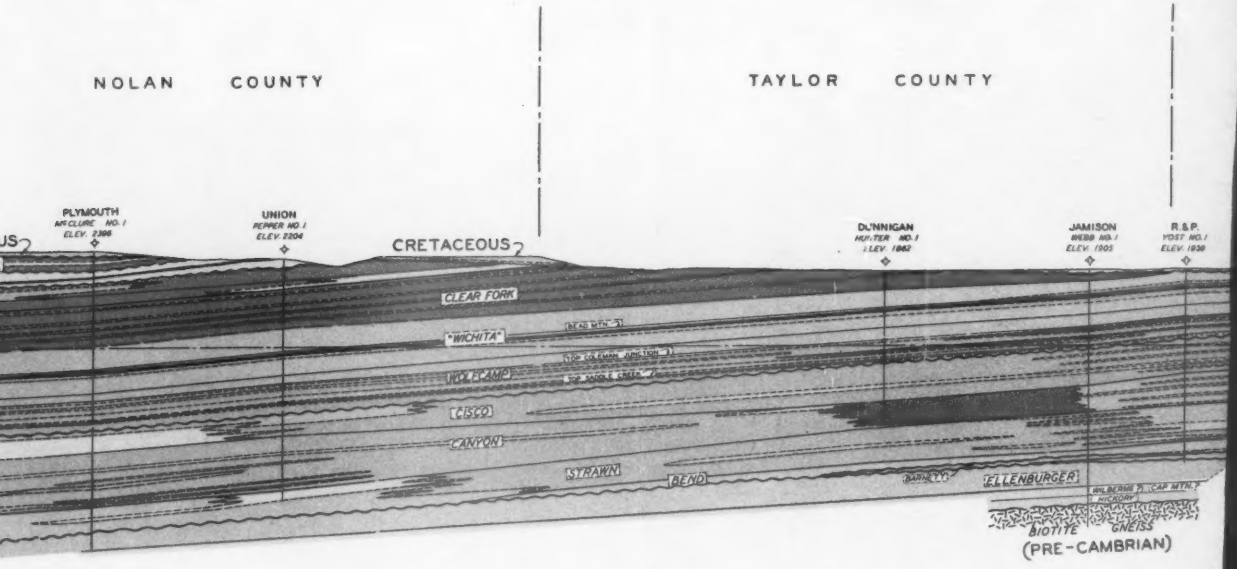


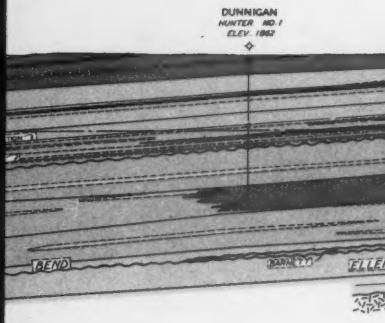
NOTE - SOLID LINES BOUND TIME UNITS

LITHOLOGY SHOWN BY THE FOLLOWING COLORS

- REEF LIMESTONE AND DOLOMITE
- STRATIFIED DOLOMITE AND LIMESTONE
- SAND AND SANDSTONE
- ANHYDRITE
- GRAY AND BLACK SHALE
- RED SHALE
- POLYHALITE
- SALT
- CHERT AND NOVACULITE

ON - COMPANY NAME
ER - FARM NAME
DRY HOLE
OIL WELL
PAY

TAYLOR COUNTY



LID LINES BOUND TIME UNITS

SHOWN BY THE FOLLOWING COLORS

IMESTONE
DOLOMITE

FIED DOLOMITE
LIMESTONE

ND SANDSTONE

RITE

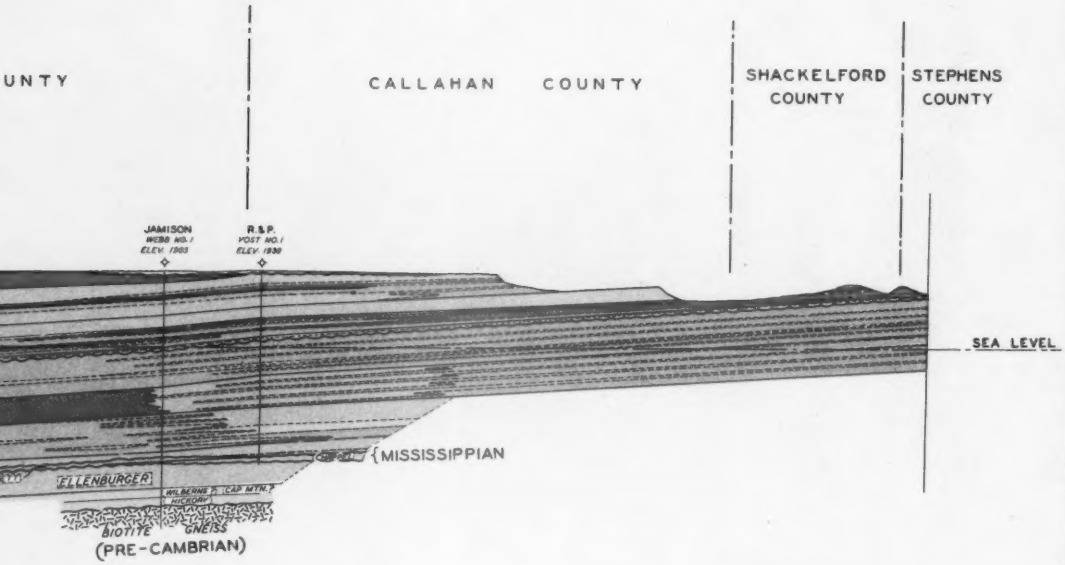
GRAY AND BLACK SHALE

RED SHALE

POLYHALITE

SALT

CHERT AND NOVACULITE



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STRATIGRAPHIC CROSS SECTION
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AMPHIBOLITES OF THE LEAD AREA, NORTHERN BLACK HILLS, SOUTH DAKOTA

BY THEODORE A. DODGE

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ABSTRACT

In the complex pre-Cambrian terrane of the Lead area of the northern Black Hills of western South Dakota is a group of amphibolites parallel to the structure of the enclosing sedimentary rocks and found at many stratigraphic horizons. These bodies have long been assumed by most workers in this area to be altered igneous intrusions.

The present study was undertaken to determine with certainty the origin of these amphibolites and to correlate their history with that of the district as a whole. Structural and petrographic evidence supports the previous conclusion, indicating that the amphibolites were originally gabbroic sills intruded into the sedimentary rocks toward the close of the dynamic metamorphism and then altered in various degrees by the movements. A zonal distribution of minerals in the sedimentary series is ascribed to the temperature effect of depth of burial and igneous intrusion, and it has been found that the amphibolites also were considerably affected by this thermal phase of the metamorphism. Hydrothermal alteration was the final chapter in the metamorphic history of the amphibolites.

INTRODUCTION

The Lead area in the northern Black Hills of western South Dakota is as noteworthy for the complexity of its geology as it is remarkable for the quantity of gold mined from its principal ore-bearing formation, the Homestake. Scattered throughout the highly metamorphosed and highly contorted pre-Cambrian sedimentary rocks are small masses of amphibolite. These bodies, both here and in other parts of the Black Hills, have been assumed to be igneous by most workers since Crosby (1888, p. 488) first definitely assigned an origin to them. In a mining area, however, where the geology of the ore deposits is exceedingly complex, assumptions bear little weight. For this reason a detailed study of these amphibolites was made with the view of ascertaining with greater certainty their origin and metamorphic history.

The field work was done during the summers of 1933 and 1934. That part of the terrane most characterized by amphibolites was mapped by plane table, and individual amphibolite bodies were studied in detail in the Homestake mine and on the surface. A few days were spent at Rochford and elsewhere in the Black Hills. Six months of the academic year 1934-1935 at Harvard University were devoted to the study of hand specimens and about 200 thin sections, and 3 months were spent in writing the doctor's thesis of which this paper is an abridgment.

The writer wishes to make acknowledgment to the Homestake Mining Company for its continued active support of this project and to the Jay Backus Woodworth Memorial Fellowship, the Carlton Thayer Brodrick Scholarship, and the Holden Fund of Harvard University for additional financial assistance.

The writer is deeply indebted to Professors Donald H. McLaughlin, Esper S. Larsen, Jr., and Marland P. Billings for invaluable help in the pursuit of this problem and particularly to Dr. James A. Noble, Chief

Geologist of the Homestake Mining Company, who contributed much time and specific material to all phases of the study. The University of Southern California and the California Institute of Technology kindly granted the writer library privileges, and Professor Ian Campbell gave freely of his time in discussing the problem.

GENERAL GEOLOGY

Separated from the main exposure of the crystalline core of the Black Hills is the Lead area of about 20 square miles within which lies the Homestake mine. This pre-Cambrian area is flanked by Paleozoic and later sedimentary rocks and cut by Tertiary intrusives. Amphibolites are found here and there in the intricately folded schists (Fig. 2). About 15 miles to the south, near Rochford (Fig. 1), is another exposure of pre-Cambrian rocks similar to those at Lead.

The pre-Cambrian rocks of the Lead area can be divided into units, some of which are well defined. There is satisfactory evidence that all except the amphibolites are sedimentary. For the purposes of the present paper a highly condensed column will serve. The upper and lower limits are those of mapping.

Pre-Cambrian Rocks

Amphibolites	Hornblende-plagioclase rocks at various horizons
Grizzly formation 3000+ feet	Phyllite
Flag Rock formation 5000 feet	Graphitic, sandy, or pyritic schists; Some quartzite (derived from chert)
———Unconformity———	
Northwestern formation up to 4000 feet	Mica schist
Ellison formation 3000-5000 feet	Upper and lower quartzites separated by mica schist
Homestake formation 200-300 feet	Quartz carbonate schist, locally much altered
Poorman formation 2000+ feet	Phyllite, with considerable ankerite

The general regional structure in the Lead area is best exemplified by the Homestake formation (Fig. 2) which has been thrown into a series of tightly compressed, complex folds, in most places plunging 15° to 40° S. Over most of the area the strikes are about N. 20° W., but in the northeastern part they are slightly east of north. The prevailing dip is steeply to the east. The more competent quartzites of the Ellison formation do not in general show the extreme rugosity of the Homestake formation.

Each major fold has minor folds on its flanks, and these in turn have others down to very small dimensions. Except locally, these subsidiary

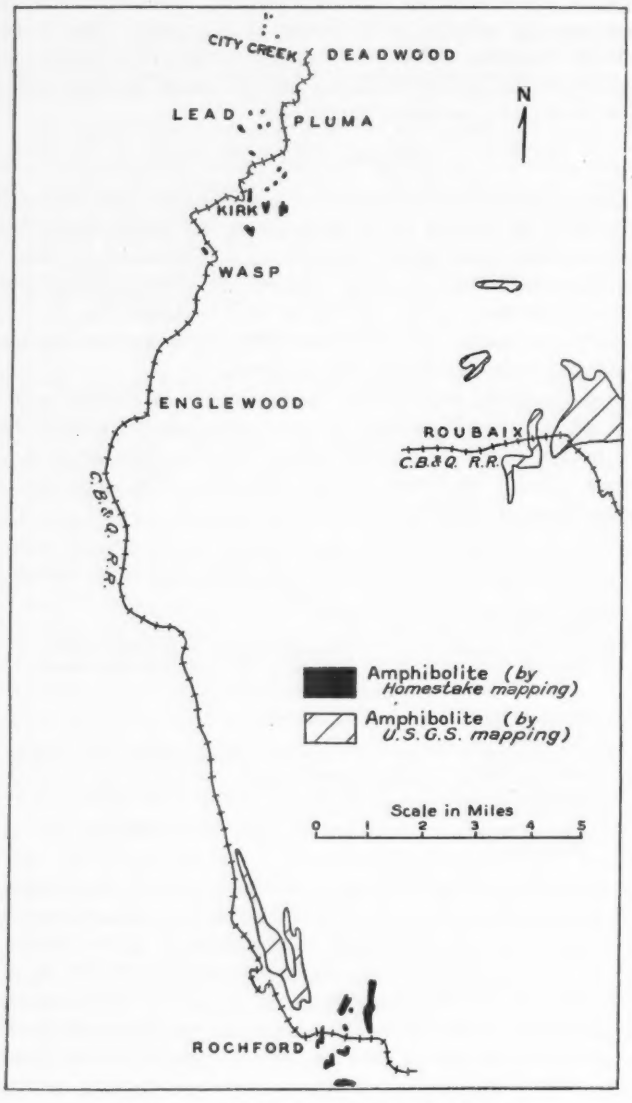

FIGURE 1.—*Sketch map, Lead to Rochford*

folds parallel the major structure. In formations with no distinctive and continuous markers, the determination of true thickness is, therefore, impossible. Furthermore, folding has produced substantial thinning along flanks and probably some thickening on crests and in troughs. The schistosity is in general parallel to the bedding, even around crests of many folds, although well defined fracture cleavage, with subordinate mica along it, is locally transverse to the bedding.

The outcrop pattern of the Northwestern formation is suggestive of an unconformity; this has been placed at the base of the Flag Rock formation. A small outcrop of pegmatite to the northeast of the map area is the only example of pre-Cambrian granite. Numerous Tertiary intrusives are present in the area, individual dikes cutting across structure in places.

METAMORPHISM

The pre-Cambrian rocks of the Lead area are, with the exception of the quartzites and carbonate beds, quartz-muscovites-biotite schists with some garnet and minor amounts of chlorite and other minerals. Some of the sediments from which these schists were derived probably had a rather peculiar composition, high in magnesia and particularly high in iron and low in alumina and particularly low in silica. Otherwise they probably constituted a fairly normal succession.

Some minor structures and textures are worthy of note. Although schistosity wraps around folds, it is not uncommon to find sharp, random blades of mica, suggestive of recrystallization subsequent to movement. Likewise many garnets cut across schistosity. The garnets are commonly full of quartz inclusions. Some of these inclusions are elongated parallel to the schistosity and are probably older than the garnet; others are equidimensional replacements of the garnet (Pl. 1, fig. 1). Garnet may also be replaced by an aggregate of quartz, sericite, and magnetite. Many of the garnets are elongated and lie parallel to the schistosity of the enclosing rock or have been rotated into oblique positions (Pl. 1, fig. 2).

Of particular interest is a zonal distribution of textures, structures, and certain minerals suggestive of increasing intensity of metamorphism toward the northeast and also downward. Whereas the Northwestern formation west of the Kirk anticline (Fig. 2) is nearly devoid of garnets, identical beds on the east side contain up to 30 per cent, and in the City Creek area to the northeast certain beds are 40 per cent garnet (Pl. 1, fig. 3). In the Ellison and Flag Rock formations, which at Rochford (Fig. 1) contain very few garnets and considerable chlorite, this same increase in garnets is seen in passing from southwest to northeast in the Lead area. Cummingtonite in the Homestake formation is much

more abundant near City Creek than to the southwest. Accompanying the increase in amount of garnet is an increase in size and prominence of the crystals. The greater prominence is due to a decrease in the amount of included material in the garnet, particularly in the rims (Pl. 1, fig. 4). Staurolite, which is found only along City Creek, shows the same feature. Increasingly coarse texture to the northeast is also shown by quartz and mica. Evidence from the Homestake mine suggests that the isograds, or division planes between these mineral zones, dip flatly southwest.

It is possible that the retrogressive changes in the garnets also show a zonal distribution. The alteration of garnet to quartz, chlorite, and magnetite is more prevalent in the southwestern part of the Lead area; the alteration to quartz alone is restricted to the central part.

This distribution of textures and minerals is difficult to explain on the basis of pressure differences in a terrane where all the evidence points to deep burial. It cannot be attributed to compositional differences since the zones cut across formational boundaries; nor does it apparently correlate with zones of greater shearing stress. Undoubtedly the zoning is primarily thermal as has been postulated for the zoning in Scotland by Barrow (1893, p. 352), Tilley (1925, p. 107), and Harker (1932, p. 185). Barrow (1893, p. 337), Barth (1936, p. 832), Billings (1937, p. 558), Turner (1938, p. 170), and numerous other workers have ascribed similar temperature zoning largely to igneous intrusion while Harker (1932, p. 179, 185) contends that the mineralogical zones are parallel to the isothermal surfaces existing in the earth at the time of the regional metamorphism, these surfaces being dependent primarily upon the depth of burial. Not far to the northeast of the staurolite beds at City Creek is an outcrop of Harney Peak pegmatite, and similar associations are found elsewhere in the Black Hills. At the same time the apparent flatness of the zones might tend to support Harker. Probably either of the above theories or a combination of both could be applied to the Lead area.

In summary, the dynamic metamorphism of the Lead area with the formation of crystalline schists occurred, at least in its later stages, in an environment characterized by rising temperatures and a domal arrangement of isothermal surfaces decreasing in intensity upward and outward from a center lying to the northeast of the Lead area. The zonal distribution of temperatures resulted in a zonal distribution of minerals and textures, the least intense zone, characterized by some chlorite and absence of garnet, lying in the southwestern part of the Lead area and the northern part of the Rochford area and the most intense zone, characterized by coarse biotite schists and abundant garnet

FIGURE 1. GARNETS IN THREE STAGES OF REPLACEMENT BY QUARTZ
Northwestern formation east of Lead. X 24.

FIGURE 2. ALTERED, ELONGATED, ROTATED GARNET
Northwestern formation near Kirk, crossed nicols. X 24.

FIGURE 3. SCHIST WITH ABUNDANT SHARP GARNETS
Northwestern formation near City Creek. X 1/3.

FIGURE 4. GARNETS WITH INCLUSION-FREE RIMS
Flag Rock formation near City Creek, crossed nicols. X 24.

TEXTURES IN THE SCHISTS

FIGURE 1. FINE-GRAINED AMPHIBOLITE. X 15

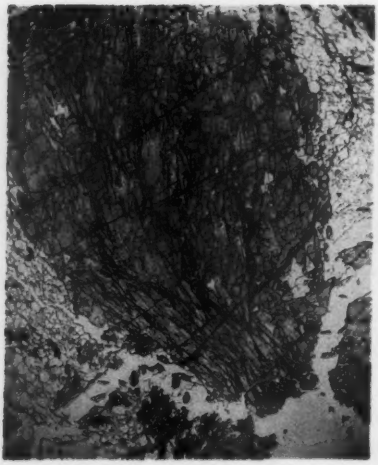

FIGURE 2. DISTORTED HORNBLENDE CRYSTAL
From intermediate amphibolite. X 15.

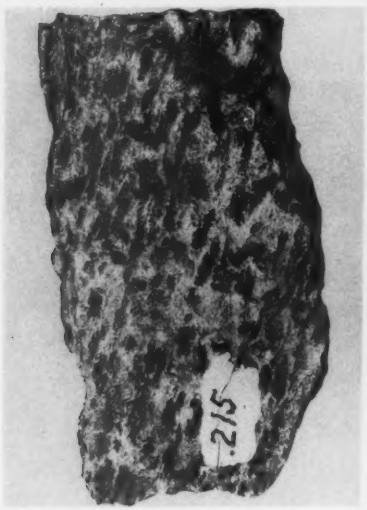

FIGURE 3. INTERMEDIATE AMPHIBOLITE. X 1/2

FIGURE 4. HORNBLENDE CRYSTAL
With S-shaped *c* axis at decided angle to long axis.
X 15.

FINE-GRAINED AND INTERMEDIATE
AMPHIBOLITE

and staurolite, lying along City Creek. Continued folding rotated some of the inclusion-rich garnets and staurolites which had appeared in their respective zones. Continued increase in temperature after the cessation of folding gave rise to inclusion-free rims of garnet and staurolite and to some recrystallization of quartz and mica. Following the dynamic metamorphism, but possibly while the temperature zoning still persisted, minor hydrothermal or retrogressive changes occurred in the schists, resulting in the breakdown of garnet.

AMPHIBOLITES

INTRODUCTORY STATEMENT

The amphibolites of the Lead area are plagioclase-hornblende bodies of a great variety of shapes and sizes but in general roughly lenticular and parallel to the regional trend of the structure and schistosity. Their mineralogical composition and their textures are varied, but they constitute a unit distinct from the enclosing schists, and their superior resistance to erosion has resulted in numerous prominent outcrops. The reader must be cautioned not to confuse these rocks with the cummingtonite schist so prevalent in parts of the Homestake formation (Gustafson, 1933).

STRUCTURAL RELATIONS

The amphibolites of the Black Hills are widespread over the pre-Cambrian terrane, and no generalization concerning their distribution can be made from the work that has been done. In the Lead area, however, most of the amphibolites are confined to the eastern half of the area mapped, but within it they are distributed haphazardly at all horizons (Fig. 2). Although this zone of amphibolite bodies is nearly parallel to the prevailing trend of the schistosity, it is decidedly crosscutting with relation to the bedding.

Examples of individual bodies that are crosscutting have been cited by Paige (Darton and Paige, 1925, p. 4) and Runner (1934a, p. 368), but a most careful search for such relationships in the Lead area has proved fruitless although on a large scale certain bodies appear to be crosscutting. Concordancy is, indeed, remarkably well developed, and some of the amphibolites wrap around folds.

The amphibolites range in width from a foot to almost 1000 feet and in length from about 30 feet to several thousand. Outside the Lead area considerably larger bodies have been mapped. The discontinuity and shape of the amphibolite bodies are unlike anything observable in the rocks known to be sedimentary, except for pods detached by tight folding from anticlinal noses and synclinal troughs.

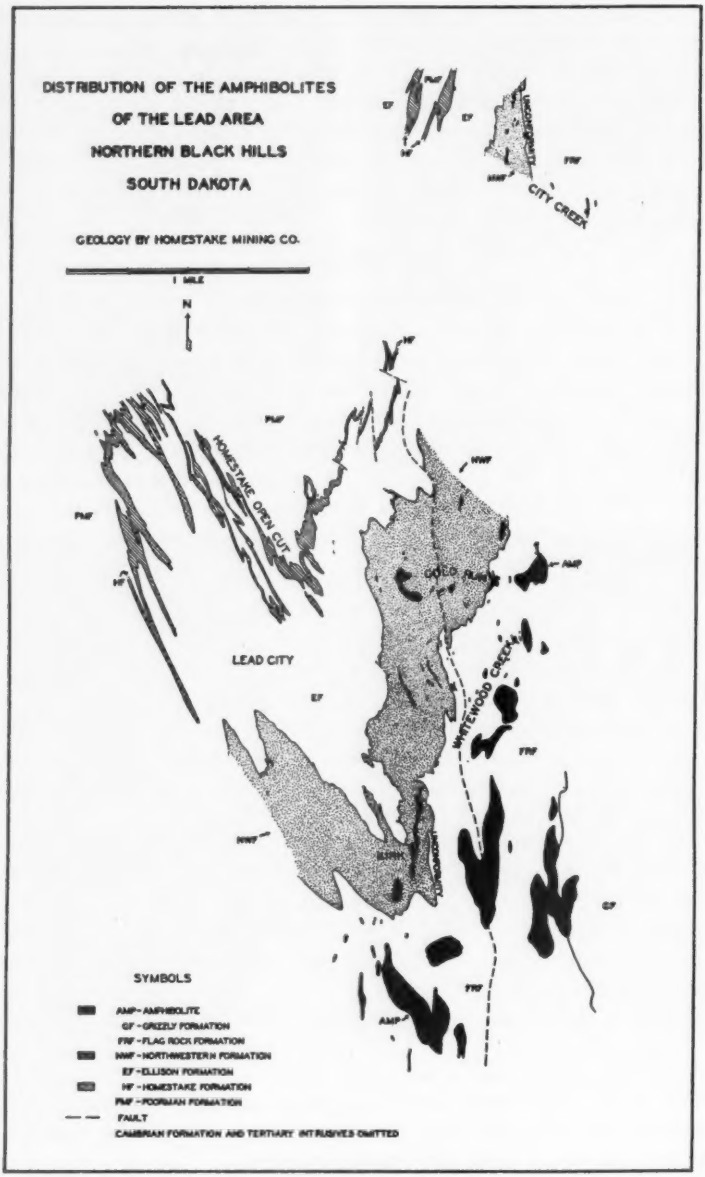

FIGURE 2.—*Map showing distribution of amphibolites of the Lead area*

PETROGRAPHY

General statement.—The definition by Holmes (1920, p. 29) of an amphibolite as "a granulose or glomero-blastic metamorphic rock, consisting essentially of amphibole and plagioclase, and often containing quartz, epidote, or garnet" covers all the unaltered bodies referred to in this paper as amphibolites with the exception of two magnesia-rich outcrops lying to the west of Lead. The principal features of most of the bodies studied are such as to permit a rough classification into three main types: (1) fine-grained, (2) intermediate, and (3) coarse.

Fine-grained amphibolites.—In outcrop hornblende is conspicuous with the long axes pitching 40° S. or SE. parallel to the regional plunge of the structure. In thin section the rock is composed of elongated, parallel crystals of hornblende in a fine groundmass of plagioclase, quartz, biotite, ilmenite, and apatite (Pl. 2, fig. 1). The minerals of the groundmass also show a well developed parallelism. The hornblende commonly includes portions of the groundmass, particularly quartz and feldspar, and clearly replaces the latter. The time relationships of the other minerals are very uncertain, but the textures observed suggest the following sequence: apatite-ilmenite (oldest), quartz, feldspar, hornblende, biotite (youngest).

Most of the hornblendes are very slender, ranging in length from 1 to 10 millimeters and in thickness from 0.1 to 2 millimeters. For the most part they are single crystals, but in a few outcrops flamboyant sheaves of hornblende are common. The most striking characteristic of the hornblende is its uniformly clear blue-green color parallel to Z. A typical crystal had the following optics: $\alpha = 1.654$, $\beta = 1.667$, $\gamma = 1.673$; $2V = 66°$, negative, $\rho > v$, $Z \wedge c = 18°$, absorption: $X < Y < Z$, pleochroism: X = straw yellow, Y = yellow green, Z = blue green. An analysis (Billings, 1937, p. 513, 556) of a hornblende from New Hampshire with almost identical optics indicates a pargasite with the formula $Ca_4\ Na(Mg, Fe)_{3.4}\ (Al, Fe)_{4.2}\ Si_{13.4}\ O_{44}\ (OH)_4$ (Harry Berman, personal communication).

The feldspar is chiefly oligoclase although both albite and andesine are also found. Twinning is visible in only a small percentage of the grains, and for statistical counts it was found necessary to use the universal stage in order to distinguish oligoclase from quartz (Dodge, 1936; Doeglas, 1940). Grain size is fairly uniform within a range of 0.05 to 0.4 millimeter. Most grains are of similar shape and elongated parallel to the schistosity of the rock. A large proportion of the grains show zoning, and this is almost invariably reverse (Pl. 4, fig. 4).

The quartz in these amphibolites is identical in appearance with the feldspar, but it is decidedly subordinate in amount in most bodies and is commonly found in tiny lenses with slightly coarser grain size.

The biotite is brown and pleochroic ($\beta = 1.638$ to 1.656). It is present in blades with good parallel orientation which may wrap around hornblende crystals or may cut into hornblende crystals apparently replacing them. In many specimens the biotite is in bands.

An intergrowth of magnetite and ilmenite is found in all specimens in small grains strung out parallel to the schistosity. Apatite is observed as small colorless prisms in most amphibolites. Other accessories such as sphene, chlorite, carbonate, pyrite, and pyrrhotite are distinctly subordinate and for the most part are probably products of hydrothermal alteration.

This fine-grained type of amphibolite outcrops in general as rather narrow bodies.

Intermediate amphibolites.—A somewhat more common type of amphibolite is characterized by coarse hornblende, conspicuous in hand specimen. This type is found in the bodies of intermediate and large size. (Fig. 2).

In thin section both large and small hornblendes are observed. The large are the more abundant and are commonly stubby, the difference in size being one of thickness rather than length. They are rounded or pointed at the ends giving an oval shape to the whole grain (Pl. 2, fig. 2). This is in part due to curving of the *c* axis. They are roughly parallel and fairly uniform in size (Pl. 2, fig. 3). The parallelism, however, does not necessarily apply to the *c* axis which may be at a decided angle to the long axis of the crystal except at the margins (Pl. 2, fig. 4). The crystals are full of inclusions of groundmass, and most of them are frayed, with numerous small crystals along their sides and trailing off the ends. The small hornblendes not in contact with the large ones are parallel to their boundaries nevertheless, and the schistosity of the rock as a whole wraps around the large hornblendes.

Optically the coarse hornblende is somewhat paler than the fine and is of slightly lower index, larger extinction angle, and slightly higher birefringence.

The other minerals and textures of this coarse-hornblende variety of amphibolite are identical with those of the fine-grained type already discussed.

Coarse amphibolites.—In the Lead area amphibolite made up of both coarse hornblende and feldspar is much less common than the two previous types, but its presence at the center of some of the large bodies is of interest, and at Rochford (Fig. 1) it is the most abundant variety found.

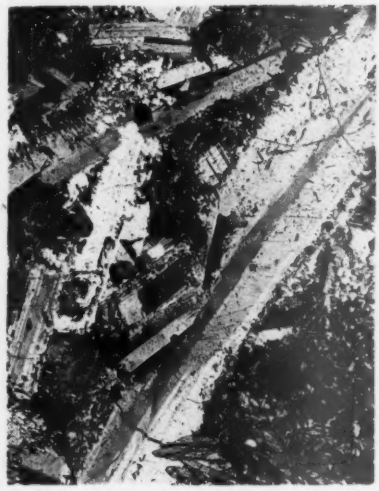

FIGURE 1. INTERGROWTH OF ALBITE-OLIGOCLASE LATHS
Crossed nicols. X 24.

FIGURE 2. HORNBLENDE WITH BRIGHTLY COLORED RIM
Groundmass of feldspar, ilmenite, apatite, and biotite. X 24.

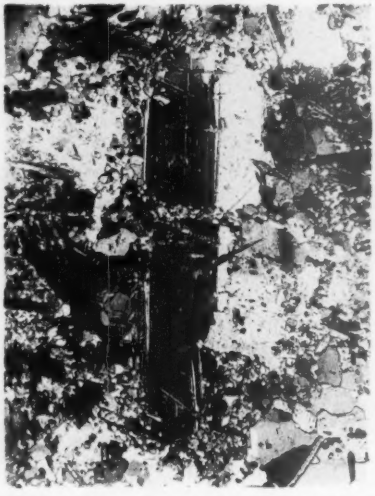

FIGURE 3. ALBITE LATH CUT BY A BAND OF FINE OLIGOCLASE
Crossed nicols. X 24.

FIGURE 4. COARSE AMPHIBOLITE FROM ROCHFORD
Crossed nicols. X 24.

COARSE AMPHIBOLITE

FIGURE 1. ALBITE LATH WITH WISPS OF HIGHER INDEX MATERIAL (INCIPIENT REPLACEMENT?), COARSE AMPHIBOLITE
Crossed nicols. X 24.

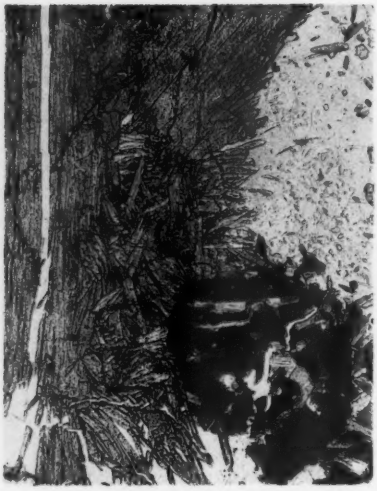

FIGURE 2. ILMENITE, POSSIBLY IN SHAPE OF FORMER CRYSTAL
Coarse amphibolite. X 24.

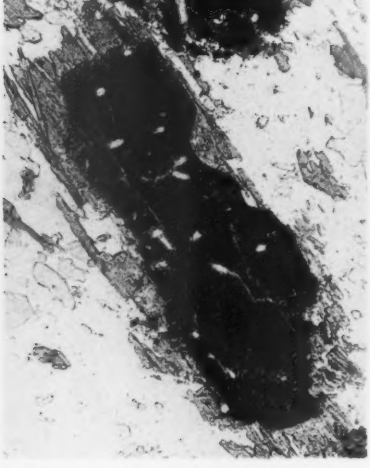

FIGURE 3. ILMENITE LATTICE WORK IN HORNBLENDE CRYSTAL
Coarse amphibolite. X 36.

FIGURE 4. REVERSE ZONING IN FELDSPAR
Fine-grained amphibolite, crossed nicols. X 72.

SPECIAL TEXTURES IN AMPHIBOLITE

As with the two preceding types, the most conspicuous mineral in hand specimen is hornblende, showing a fair linear parallelism. In section (Pl. 3, figs. 1, 2) the rock is a hornblende-albite (or oligoclase) amphibolite with minor amounts of biotite, ilmenite, and apatite. The hornblendes are in both large and small grains, intergrown with each other to a certain extent and with the feldspar, which they clearly replace. Much of the feldspar is in regular laths with scalloped edges, but all gradations are found between these and extremely irregular laths blotched with fine-grained feldspar (Pl. 3, figs. 3, 4), or containing shadowy wisps of higher-index material, suggesting incipient replacement (Pl. 4, fig. 1). The laths average 1 or 2 millimeters in length and are albite-oligoclase. They are intergrown with themselves and with hornblende. The fine feldspar (less than 0.5 mm.) is oligoclase and is present as a groundmass or as patches or isolated grains replacing the coarse feldspar. It is of slightly higher index than the coarse.

Biotite commonly makes up 10 per cent of these amphibolites in Lead but is much less abundant at Rochford. It is found in medium-sized blades, ordinarily in clusters and without any noticeable orientation. There is little quartz. Ilmenite is present in small blades or large patches (Pl. 4, fig. 2), and apatite in small needles is a minor constituent in every specimen examined.

Most of the large hornblende crystals are of the pale variety observed in the intermediate amphibolites with narrow borders of the strongly colored type following their periphery (Pl. 3, fig. 2). All the small crystals are strongly colored. In certain outcrops the pale core of a hornblende crystal may be largely obscured by the presence of a lattice work of ilmenite (Pl. 4, fig. 3).

Augite has been reported by Irving (1899, p. 187) from a coarse amphibolite west of Lead. Five sections were examined by the writer from outcrops at this locality, and no augite was found. It seems likely that Irving, as well as some later workers, mistook pale hornblende for augite.

Thin sections of specimens from large amphibolite bodies from other parts of the Black Hills, notably from Roubaix, Squaw Creek, and Doll's Ranch showed no features very different from those noted above for the amphibolites with coarse hornblende and feldspar at Lead and Rochford.

Zonal effects.—The descriptions just given apply to most of the amphibolite bodies of the Lead area and Rochford irrespective of location. In addition, however, there are certain minor petrographic features which bear a definite relation to the mineralogical zones noted in the schists.

Beta of hornblende from amphibolites in the chlorite zone at Rochford

ranges from 1.635 to 1.665 with the average about 1.655. In the vicinity of the town of Lead beta is about 1.670; in the City Creek area to the northeast it is about 1.680. With the increase in index is an increase in the intensity of the color, in the City Creek area even the large hornblendes being deep blue-green. The zone with hornblende of highest index coincides with the staurolite zone in the schists.

In a general way the increase in beta of hornblende is accompanied by an increase in the calcium content of the plagioclase. At Rochford most of the feldspar is albite. In Lead oligoclase is the commonest type of feldspar. Farther to the northeast andesine is found in parts of some bodies while in the City Creek region andesine is as abundant as oligoclase.

Garnet is a conspicuous mineral in many amphibolites. Aside from a few bodies in the center of the area which have been altered by hydrothermal solutions, garnet amphibolites are found only to the northeast, and all the bodies in the City Creek area contain garnet. It may make up as much as 20 per cent of these bodies.

In addition to the zonal distribution of indices and minerals there is a rough zonal distribution of grain size with increase toward the northeast. This applies particularly to the hornblende.

Summary of petrography.—The petrography of the amphibolites of the Lead area suggests an igneous origin. The two principal accessories, ilmenite and apatite, are unknown in the sedimentary series. The ilmenite lattice in the centers of some hornblende crystals suggests the derivation of the hornblende from augite. The general texture of the coarse feldspar is not unlike that of an igneous rock, and the presence of the coarse type in the large bodies grading to the fine-grained type in the small bodies is in accord with this concept. This latter feature will be discussed more fully in dealing with the metamorphic history of the amphibolites.

COMPOSITION

The approximate mineralogical compositions of typical specimens of the three types of amphibolite are given in Table 1.

The intermediate type is the most uniform in mineralogical composition, and the fine-grained type shows the greatest extremes, particularly in hornblende, which ranges from 30 per cent to 75 per cent. In general the coarse amphibolite has less hornblende and more feldspar than the other two types.

Goldich (1938, p. 48) has published the only analysis of an amphibolite from the Lead area. Unfortunately it is from a body that has undergone extensive hydrothermal alteration with consequent reduction in

silica and increase in iron. However, the close check with Goldich's analysis obtained by calculating the chemical composition of this particular amphibolite from its mineralogical composition makes it possible to place some reliance on calculated compositions of unaltered amphibolites.

TABLE 1.—*Mineralogical compositions of amphibolites*

	In volume per cent		
	Fine	Intermediate	Coarse
Hornblende	40	50	25
Albite	.....	.....	20
Oligoclase	35	10	30
Andesine	.....	25	.....
Quartz	6	1	2
Biotite	7	1	12
Chlorite	.....	8	2
Ilmenite	7	5	7
Apatite	5	tr.	2

The calculated composition of an average coarse amphibolite is 50 per cent silica, 18 per cent alumina, 14 per cent total iron oxide, 4 per cent magnesia, 5 per cent lime, and 4 per cent soda with minor amounts of titanic oxide, potassa, and water. An average fine-grained amphibolite appears to have slightly less alumina and more lime. The amphibolites containing garnets are low in silica (45 per cent) and high in iron (20 per cent).

Many analyses of amphibolites have appeared in the German literature. These, with few exceptions, are more uniform than those calculated for the amphibolites of the Lead area, but they agree well with the latter except for lower iron. The same is true of analyses of amphibolite proved beyond doubt to be derived from mafic igneous rocks given by Adams and Barlow (1910, p. 108), Eskola (1914, p. 109), Teall (1885, p. 137), Wurm (1926, p. 69), and Buddington (1939, p. 13). Going directly to averages of analyses of various types of igneous rocks, such as those listed by Daly (1933, p. 9, *et seq.*), it is found that the calculated analyses do not come far from those of gabbros (or dolerites) and diorites.

For purposes of comparison the approximate compositions of various extreme types of sedimentary rocks in the Lead area have been calculated in an attempt to duplicate the composition of the amphibolites. Certain of these indicate peculiar sediments, but they would make equally peculiar

igneous rocks, and nothing approaching the composition of the amphibolites has been found by this method. This does not mean that sediments of such a composition are unknown. Adams and Barlow (1910, p. 87) have traced impure calcareous beds into amphibolite, and sediments of a tuffaceous nature might have compositions very similar to those of the amphibolites. In fact, Runner (1934a, p. 368; 1934b, p. 132; 1937) has suggested that impure calcareous beds were the original rock from which some of the amphibolites of the Black Hills have formed, using as evidence the presence of carbonate veins in some amphibolites and a supposed coincidence of occurrence of amphibolites and calcareous beds.

Although no beds of the requisite composition are found in the Lead area, many of the sediments are indeed peculiar, and it would be possible to maintain that the proper sort of alteration could change some of these sediments into amphibolite. Also it would be possible to hold that all sediments of the requisite composition had been converted into amphibolite. No very tangible answer can be obtained, therefore, from considerations of composition alone.

SUMMARY OF EVIDENCE OF IGNEOUS ORIGIN

The petrography and the calculated compositions of the amphibolites of the Lead area are such that they could well be derivatives of igneous rocks. It has just been demonstrated, however, that these considerations alone do not furnish conclusive proof, and it is necessary, therefore, to fall back upon the broad features of distribution and structure already discussed. Although the individual amphibolite bodies conform to the structure, the zone as a whole is crosscutting. Furthermore, the only known sedimentary bodies similar in shape and showing such discontinuity are pods detached from anticlinal noses and synclinal troughs, which clearly show by their position their structural origin. The writer is convinced, therefore, that the amphibolites of the Lead area were originally igneous rocks of gabbroic or doleritic nature intruded as dikes or sills into the sedimentary rocks.

METAMORPHIC HISTORY OF THE AMPHIBOLITES

Time relations.—As early as 1885 Teall showed that amphibolite could form from dolerite after the complete solidification of the igneous rock. On the other hand according to Eskola's (1920) facies scheme the end product might be the same whether intrusion occurred during or before folding. Most of the mineralogical evidence points to intrusion of the mafic sills of the Lead area before the cessation of major folding movements since even the most massive varieties show some alignment of the hornblendes and physical breakdown of feldspar. However, it seems

somewhat unlikely that an amphibolite zone parallel to the regional schistosity but at the same time cutting across the regional structure could have been intruded while the sediments were flat-lying. It is probable, therefore, that the amphibolites were intruded into the sediments of the Lead area after the major structure had formed. The survival of textures like those of igneous rocks in the large bodies suggests that the amount of movement after intrusion was not excessive. Nevertheless, the linear parallelism of the hornblendes, in harmony with the regional plunge of the structure, and the presence of many small bodies of very schistose rock make it seem likely that not only differential pressure but movement persisted after intrusion. At the time intrusion occurred, movement and stress were probably not great, at least not great enough to affect materially the intruded bodies or to prevent the formation of random feldspar.

Connolly (1927, p. 12) has suggested two periods of injection to explain the differences in the amount of metamorphism, but the writer is inclined to relate these differences to the size of the bodies and their location with respect to intensity of stress as discussed in the following section.

Changes in texture.—Although none of the original igneous rock from which the amphibolites were derived is found in the Lead area, it is possible that the massive phases of the coarse amphibolite are not far removed. Thus the lath-shaped feldspar of the large bodies may be, in part at least, inherited from the original rock. Although the size, shape, and distribution of most of the hornblende is probably entirely the result of metamorphic processes, the lattice core of opaque mineral seen in many hornblende crystals of the body east of Kirk (Pl. 4, fig. 3) may represent the precipitation of magnetite in the change of some mineral to hornblende. This earlier mineral may have been brown hornblende or augite and may represent an original mineral of the igneous rock. The clusters of ilmenite with a suggestion of rhombohedral shape (Pl. 4, fig. 2) in the more massive parts of the amphibolite bodies may also represent relics from the original rock. So may apatite, which is present in broken prisms replaced by other minerals.

In the intermediate and fine-grained types of amphibolite it is probable that no textures of the original igneous rock persist.

It is a general rule that the fine-grained amphibolites are the narrowest bodies, the bodies with intermediate texture are those of intermediate size while coarse amphibolite is found only in the largest bodies. There is a greater abundance of fine hornblende in those zones in the coarse amphibolite in which the large feldspars are most broken down into fine feldspar. Furthermore, the sheared and broken hornblendes (Pl. 2, figs. 2,

4) in the amphibolite of intermediate type obviously were gradational into and less stable than the smaller crystals parallel to the schistosity. All these data make it plausible to imagine a complete transition between coarse amphibolite through amphibolite with coarse hornblende but fine feldspar to fine-grained amphibolite. Only along the borders and certain shear zones did the large amphibolite bodies yield excessively to the stresses of the folding except where differential stress was particularly intense. The intermediate bodies changed more and lost whatever coarse feldspar they contained although the shearing was not severe enough to prevent the recrystallization and adaptation to the movement of the large hornblende crystals. In the small bodies and in those larger bodies which were in a position to receive the full effect of the differential stresses of the folding even the hornblende could not maintain a large size and recrystallized into parallel grains, giving the rock a very schistose texture.

This interpretation of the history of the amphibolites is essentially in harmony with the conclusions of Crosby (1888, p. 488), Van Hise (1889, p. 230), Irving (1899, p. 187), Paige (Darton and Paige, 1925, p. 4), and others in the Black Hills. Similar occurrences have been explained in the same way in many parts of the world.

Changes in composition.—Insufficient evidence is available in the Lead area to form the basis for a discussion of the probable changes in mineralogical composition which occurred during the metamorphism, such as has been given by Eskola (1914, p. 109) for the amphibolites in Finland. The higher percentage of hornblende and the lower percentage of feldspar in the fine-grained amphibolites at Lead indicates the adaptation of the mineral assemblage to the stress environment, but beyond this it is uncertain to what extent the mineral composition of the amphibolites changed in response to the stress and temperature changes of advancing metamorphism.

Adjustment to rising temperatures.—The relationship between certain minor petrographic features of the amphibolites and the metamorphic zones defined in the schists has been described. Wiseman (1934, p. 354) has made a thorough study of such changes in the epidiorites of Scotland and believes them to be due to mineralogical rearrangements in response to the increasing temperature of metamorphism. Analysis of hornblende from an epidiorite (amphibolite) in the chlorite zone showed low alumina and alkalies and high calcium. This hornblende had an index like that of the hornblendes at Rochford. The analysis of a hornblende from the garnet zone (index a little higher than that of the hornblendes of the garnet amphibolites at City Creek) shows higher alumina and alkalies and slightly lower lime. Wiseman ascribes these changes to the disappear-

ance of primary chlorite in the garnet zone. This cannot be used as an explanation of the changes in the Lead area as chlorite is inconspicuous except as an alteration product. Nevertheless, whatever the chemical interchanges involved, it is probable that the feldspar high in anorthite and the hornblende of high index were stable at higher temperatures than the albite feldspar and hornblende of low index. Likewise it is probable that the amphibolites in the City Creek region were originally like those lying to the southwest but acquired garnet during the high-temperature stage at the end of the regional metamorphism.

In spite of this apparent adjustment of the minerals of the amphibolites to the zonal distribution of temperatures in the Lead area, there is considerable evidence of lack of attainment of equilibrium. Thus most of the coarse hornblende of the intermediate and coarse amphibolites is pale green, and the fine hornblende is bright green. The coarse crystals commonly have a rim of bright hornblende (Pl. 3, fig. 2). It is probable that the pale hornblende is lower in alumina or alkalies than the bright. Several explanations are possible. Most uralite is pale in color. The coarse hornblende although not necessarily representing in size, shape, and location the original augite of the rock might have formed largely at its expense. Later growth during metamorphism might have been more at the expense of the feldspar, giving an aluminous hornblende. Another, though similar, explanation would be that the growth of the bright hornblende occurred at a higher temperature than that of the pale; or it may have occurred at a time when oligoclase and andesine were forming from albite and oligoclase, and the necessary constituents, such as alkalies perhaps, were set free to give bright hornblende.

Failure to attain equilibrium is also seen in the fact that the fine feldspar resulting from the shearing and replacement of the coarse feldspar is of higher index, and therefore more calcic, than the coarse. This increase in calcium in the later feldspar indicates progressively higher temperatures during the change from coarse amphibolite to fine. Furthermore there is reverse zoning in the small feldspar grains (Pl. 4, fig. 4); that is, the outer zone of the grain is higher in lime than the inner.

In summary, therefore, it is apparent that the amphibolites responded to the increasing temperatures of the later stages of the regional metamorphism. Although they did not attain complete equilibrium, they responded sufficiently to give recognizable differences in the various zones defined in the schists.

High-temperature hydrothermal action.—Several amphibolite bodies in the Lead area have a mineral composition markedly different from the others, and some have peculiar marginal schists.

The small body lying along the contact between the Northwestern and Flag Rock formations and outcropping in Gold Run Gulch east of the town of Lead (Fig. 2) will serve as an illustration. It is made up of bands of amphibolite of differing compositions lying parallel to each other and to the structure of the schist. All gradations are found between a rock made up of 60 per cent hornblende and only a slight excess of quartz over feldspar and a rock with all of the hornblende replaced by random biotite in the presence of a considerable excess of quartz (Pl. 5, fig. 1). It is probable that the biotite type of rock is lower in silica, magnesia, and lime and higher in iron than the hornblende type.

Sixty feet west of the contact of this amphibolite the rocks are the normal banded garnet-mica schists of the Northwestern formation. At 50 feet there is a little sericite, and occasional grains of sphene are present, a mineral almost unknown in the Northwestern formation. At 25 feet the rock contains several per cent of rather coarse chlorite replacing the biotite and other minerals, and a good deal of fine sericite, both in greater amounts than usual. In the last 4 feet feldspar appears and increases until at a foot from the contact it makes up a third of the rock. Accompanying the increase in feldspar is a great decrease in mica and a reduction in grain size. Tourmaline increases, and apatite and carbonate make their appearance. Within 2 feet of the contact the rock is dense and uniform, resembling a quartzite, and in the last 3 inches is made up of bands of stubby and fibrous hornblende with optics close to those of the hornblende of the amphibolite (Pl. 5, fig. 2). Quartz and feldspar with sharp normal zoning make up 70 per cent of this rock. Calcite, garnet, and pyrrhotite are found along the contact.

There can be no doubt whatever that these peculiar marginal schists were originally sedimentary. All gradations between them and the normal schist can be found, and certain sedimentary structures such as graphitic banding have been preserved in places.

Adjacent to other peculiar amphibolite bodies in the Lead area which are characterized by chlorite, garnet, and large hornblendes in random orientation, the schists have more and larger garnets. In certain amphibolites hornblende makes up 80 per cent of the rock and in some bodies is apparently later than the chlorite. Other bodies are cut by zones of biotite and cummingtonite, the latter mineral being found in some of the marginal schists. The schists along several amphibolite contacts look bleached and in thin section are seen to be composed largely of feldspar and quartz, the biotite having been removed.

The altered schists may be present on one side of an amphibolite body and not on the other, and they commonly extend farther along strike from the end of a body than they do across strike from the center.

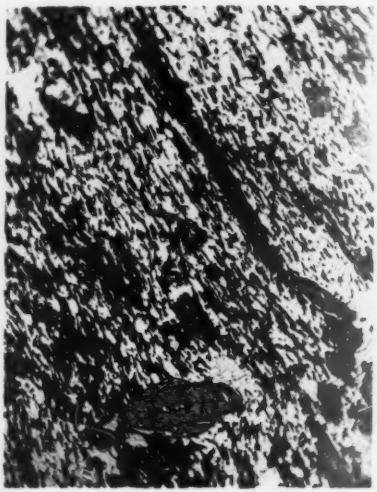

FIGURE 1. AMPHIBOLITE RICH IN BIOTITE AND QUARTZ. X 15

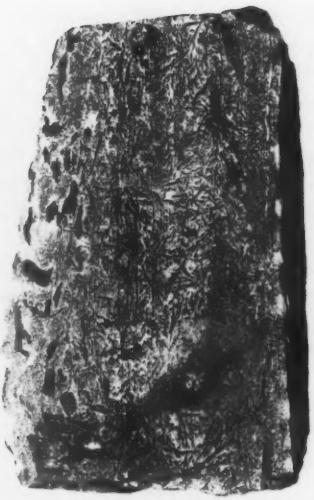

FIGURE 2. SCHIST ALTERED AT AMPHIBOLITE CONTACT. X 1/2

FIGURE 3. HORNBLENDE CRYSTAL ALTERED TO CHLORITE AND MAGNETITE. X 36

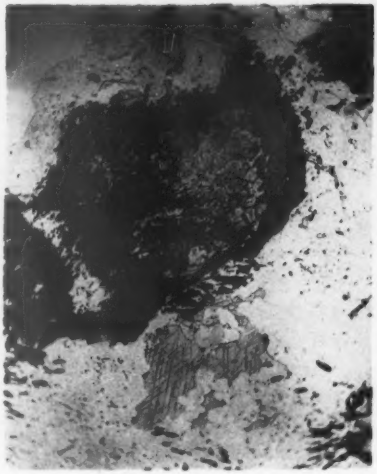

FIGURE 4. HORNBLENDE AND FELDSPAR REPLACED BY CARBONATE. X 15

HYDROTHERMAL TEXTURES

Nearly all these amphibolite bodies are higher in quartz than normal but lower in total silica because of the high percentage of biotite, chlorite, and garnet. From the chemistry alone it might be possible to postulate an original composition different from that of the normal amphibolite, but the association of the peculiar marginal schists with these particular bodies, the redistribution of minerals, and the presence of hornblende and biotite in random orientations in both the marginal schists and the amphibolites point to high-temperature hydrothermal action after (but probably not long after) the cessation of all folding movements. Somewhat similar alteration has been described in the Belt rocks of Montana by Gibson and Jenks (1938). The alteration of amphibolite to biotite schist by granitic solutions has been noted in the Adirondacks by Buddington (1939, p. 176). The following mineralogical and chemical changes due to metasomatism observed in greenstones in Cornwall by Tilley (1935) are similar to those just described: (1) mineralogical—introduction of biotite, almandine garnet, quartz, and cummingtonite and eventual disappearance of hornblende; (2) chemical—addition of iron and alkalies and removal of lime and in some cases silica.

Aside from altering the amphibolites and their marginal schists these solutions filled many of the cross fractures which are common in the amphibolites, the resulting veins being roughly normal to the linear direction of the hornblendes. Most characteristic are veins about 2 feet long and less than an inch wide containing balls of radial chlorite flakes, quartz, and calcite in that sequence. Slightly larger and more abundant in the large amphibolite bodies are veins of feldspar commonly present as diamond-shaped plates and prisms, many of which exceed 2 centimeters in diameter, embedded in fine-grained chlorite. Most of the feldspar is in the albite range near oligoclase and may contain replacement relics of oligoclase (or andesine), the feldspar of the rock. One vein in an andesine amphibolite, however, contained some labradorite with normal (igneous-type) zoning. Also present in many veins are calcite, tourmaline, and columbite-tantalite, the last-mentioned being a characteristic of some of the pegmatites associated with the Harney Peak granite. At Rochford the feldspar of these veins is almost pure albite.

Numerous cross veins contain asbestiform hornblende having the same optics as the hornblendes of the enclosing rock. Other minerals of the cross veins include clinozoisite, ankerite, biotite, cummingtonite, and anthophyllite.

It is probable that most of the minerals of these cross veins were derived from the adjacent rock although a few, such as columbite-tantalite, were brought in from outside. Thus the cross veins appear to be the result of the same sort of hydrothermal action which altered

certain of the amphibolite bodies and their marginal schists. The solutions were apparently at a rather elevated temperature, introduced only minor amounts of distinctive minerals, and accomplished most of their work by redistributing locally some of the minerals already present.

The hydrothermal action responsible for these veins and for the alteration of the amphibolites, although particularly characteristic of the amphibolite bodies, was not entirely restricted to them. Both cummingtonite schist and quartzite, the two other competent rocks of the Lead area, have cross veins containing minerals suggestive of high temperatures and little introduction of material. Evidences of hydrothermal alteration, such as the silicification of garnet, are to be found in many places in the schists, and the fact that it differs from that found in the rocks marginal to the amphibolites is merely due to the differences of the materials with which to work. The particular concentration found next to the amphibolite bodies might be due to a greater permeability along the contact between the massive amphibolites and their enclosing schists.

Low-temperature hydrothermal action.—In contrast with the hydrothermal changes described above, which produced minerals and textures almost identical with those of the regional metamorphism, there are zones of alteration found in some of the amphibolites characteristic of low-temperature hydrothermal action. Chlorite and calcite are the predominant minerals (Pl. 5, figs. 3, 4), and these are most commonly concentrated along the borders of the amphibolites, particularly of the larger bodies, or along shear zones.

At Rochford alteration is much more prevalent than at Lead, and nearly every amphibolite body shows progressively more intense alteration from the center out. All gradations exist between normal amphibolite and a rock composed entirely of chlorite and carbonate. In many cases hornblende is the first mineral to disappear, its place being taken principally by chlorite. Epidote is not uncommon at Rochford and appears to be an alteration mineral.

Along the western margin of the Lead area there is a group of peculiar schists consisting of chlorite, quartz, and calcite with minor amounts of iron oxides, sphene, and apatite. It is probable that these are highly sheared and altered amphibolites.

It should be noted that change in mineralogy is much more conspicuous than change in texture in these altered amphibolites. In rocks containing no hornblende lath-shaped feldspars still survive. This is the opposite of what happened in the dynamic metamorphism of the amphibolites. Furthermore, where shearing appears to have been important, it seems to

have changed the texture of the rock not by rotation of the existing crystals but by recrystallization.

Quartz-calcite veins, with some biotite, pyrite, pyrrhotite, apatite, chlorite, and feldspar, parallel to the linear schistosity of the amphibolites are common in the Lead area and at Rochford and may possibly be contemporaneous with the retrograde alteration just described.

This low-temperature hydrothermal alteration undoubtedly was the last important chapter in the metamorphic history of the amphibolites. To what geological age it belongs, however, it is impossible to say.

Relation between zoning and hydrothermal action.—It might be possible to postulate a very rough zonal distribution of hydrothermal types in the amphibolites correlative with those suggested for the schists. Thus the high-temperature type is more common in the central and northeastern part of the Lead area, and the low-temperature type (along with strong evidence of shearing), in the southwestern part and at Rochford. The high-temperature type gives evidence of both rising and falling temperatures. Hence it might be imagined that hydrothermal activity commenced while zoning and increasing temperatures persisted and continued until the regional temperatures started to decline, but still maintained a gradient toward the southwest. The evidence is imperfect, and the theory is highly speculative. It can be true only in part.

SUMMARY

The conclusions reached by the writer in the study of the amphibolites may be summarized in the following sequence of events.

Originally flat-lying sediments were tightly folded and converted into schists, perhaps of a chloritic nature. After the formation of the major structure but before movement had ceased, a zone of sills of gabbroic or doleritic character was injected into the district. The individual bodies followed the structure of the schist although the zone itself was cross-cutting. At about the same time similar intrusions were occurring at Rochford and elsewhere in the Black Hills. Continued folding and differential stress changed these intrusives into amphibolites with different degrees of schistosity depending upon the size and location of the individual bodies. Meanwhile the temperature of the region was rising, and the chlorite schists were changing to biotite, garnet, and staurolite schists. The new minerals forming in the amphibolites under the influence of the physical forces brought into play were of types more stable at the new temperatures than their respective parents, but complete equilibrium, particularly in the larger amphibolite bodies, was not attained.

Finally the last movements ceased, and many of the sedimentary rocks recrystallized, destroying some of the evidences of their dynamic history. At a time, perhaps considerably later, but possibly while temperature zoning still persisted, hot solutions invaded the area. These produced some alteration in the sedimentary rocks and resulted in numerous mineralogical and chemical changes in certain amphibolites and their marginal schists.

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Box 49, Las Cruces, New Mexico.

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FIGURE 1. DEACON SCARP
Northwest of Golden Lake, Renfrew County, Ontario (Royal Canadian Air Force photograph).

FIGURE 2. ST. PATRICK SCARP
From White Lake tower, Renfrew County, view westward.

FAULT-LINE SCARPS

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OTTAWA-BONNECHERE GRABEN AND LAKE ONTARIO HOMOCLINE

BY G. MARSHALL KAY

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ABSTRACT

The northwest-trending Ottawa-Bonnechere graben is separated from the Lake Ontario homocline, the northern border of the Allegheny synclinorium, by the block-faulted Madawaska Highlands of central Ontario. Ordovician sediments are preserved as infaulted outliers in the graben and form a plain adjoining the resurrected pre-Paleozoic Cashel peneplane, the northern belt of the homocline. The stratigraphy in the two districts is similar, and the sediments must have been continuous originally. Northeast-trending monoclines cross the Paleozoic plain of the homocline; their age is unascertained. Thick Paleozoic rocks concealed the pre-Cambrian of the southern Canadian Shield at the time of faulting of the Ottawa-Bonnechere graben, in the early Tertiary. The faults have trends corresponding to those of joints of earlier origin and have displacements of as much as 1500 feet.

INTRODUCTION

The Allegheny synclinorium, a broad, southwest-plunging structure lying in the north between the Adirondack block mountains and the Cincinnati arch (Fig. 1), has the Lake Ontario homocline as its northern limb. The peneplaned pre-Cambrian rocks of the Canadian Shield have been de-

formed by the normal faulting of the Madawaska Highlands and the Ottawa-Bonnechere graben, and the former is connected with the Adirondacks by the crystalline corridor of the Frontenac arch. Northeast of the arch lies the St. Lawrence basin of Cambrian and Ordovician sediments.

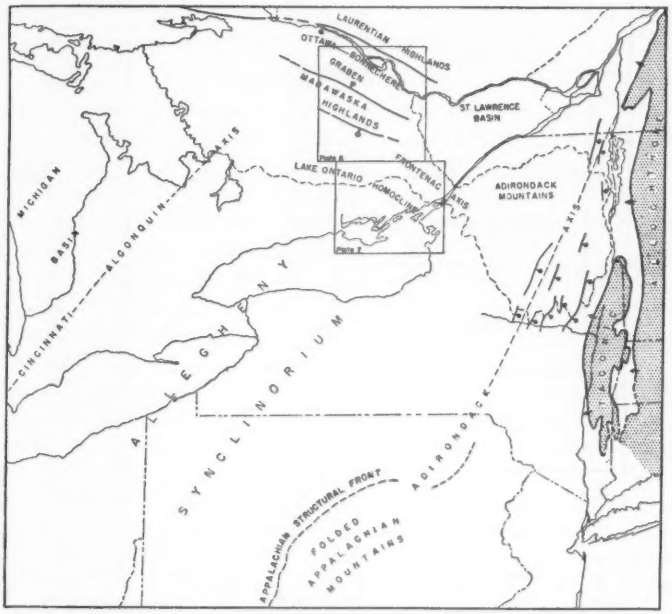


FIGURE 1.—*Structural provinces of eastern United States and adjacent Canada*
With location of area

The stratigraphy of the Paleozoic rocks in the northern Allegheny synclinorium has received considerable discussion, but the significance of the sediments infaulted within the Shield and the structural character of its southern margin have received little attention. The present stratigraphic and areal study was carried on chiefly in a belt between eastern Lake Ontario and that part of the Ottawa valley in Renfrew County, Ontario, and Pontiac County, Quebec, where Paleozoic outliers are extensive and numerous.

A grant from the Penrose Bequest of The Geological Society of America supported the completion of field work. The writer was assisted in the

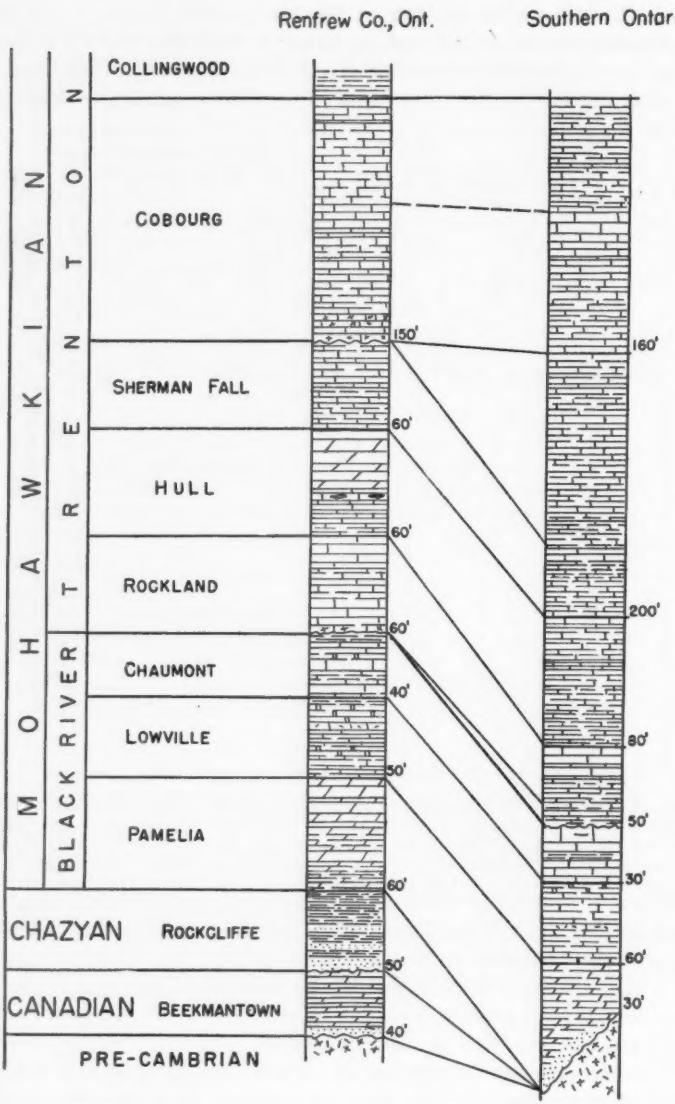


FIGURE 2.—*Columnar sections of Paleozoic rocks in Renfrew County and in southeastern Ontario*

field by several students in Columbia University, particularly R. V. Colligan, Peter Milton, and Donald Rockwell; W. O. Clift and D. E. Koons drafted most of the illustrations. F. N. MacDougall, Superintendent of Algonquin Provincial Park, and the staff of the Ontario Forestry Branch gave information and assistance that materially aided in understanding the unsettled interior of central Ontario and in determining elevations of higher areas.

STRATIGRAPHY

INTRODUCTORY STATEMENT

Pre-Cambrian and Ordovician rocks outcrop in the region between the eastern end of Lake Ontario and the Ottawa River. The distribution and sequence of the older crystalline rocks have been described in varying detail (Adams and Barlow, 1910; Miller and Knight, 1914; Ells, 1907). The present study includes a description of an area of granite boulder-bearing conglomerate in the Shannonville inlier. The interpretation of structure in areas of the pre-Cambrian rocks depends considerably on geomorphic evidence; hence the recognition of the belts of resistant formations and their structure is important in the recognition of later deformation.

The Paleozoic sediments dealt with are restricted to the Ottawa-Bonnechere graben and the southern part of the Lake Ontario homocline (Fig. 1) and are separated by pre-Cambrian rocks of the Madawaska Highlands and Cashel peneplane (Pls. 6, 7). The sections in the two regions (Fig. 2) are for the most part similar; the formations will be discussed and compared. There has been little written on the stratigraphy in the north (Ells, 1907), though equivalent beds have been detailed in the lower Ottawa valley (A. E. Wilson, 1937; M. E. Wilson, 1924). More is known of the Ordovician sediments along the north shore of Lake Ontario (Baker, 1916; Kay, 1937; Sproule, 1936; Young, 1937). The northern area will be described more fully, for the structural interpretation is dependent on stratigraphy that has been little discussed.

CANADIAN SERIES

Beekmantown dolomite.—The Beekmantown dolomite, the oldest sedimentary formation, is poorly exposed in the Renfrew district and absent in the Lake Ontario homocline. The beds are probably equivalent to the March dolomite (A. E. Wilson, 1937, p. 46) in the Ottawa district, but the correlation has not been demonstrated. The dolomite is best shown on the north side of Allumette Island in lots 9 and 10, con. I, 4 miles west of Chapeau, where 23 feet of a probable thickness of 50 feet is exposed (Table 1). Small exposures are scattered along the western end of the island. Neither exposures nor drift blocks of the Beekmantown have

been recognized in areas southwest of the Allumette outlier. Because of its relative resistance one might expect to find outcrops if it were present, and the interval between younger beds and the pre-Cambrian seems too small to accommodate any considerable thickness. The con-

TABLE 1.—*Section west of Chapeau, Allumette Island, P. Q.*

Formation description	Thickness in feet	
	of unit	to base of section
CHAZYAN series		
ROCKCLIFFE formation:		
Buff and gray, coarse-textured, heavy-ledged cross-laminated quartz pebble-bearing sandstone; forming terrace west of road; exposed	5	64
CANADIAN series		
BEEKMANTOWN dolomite:		
Unexposed, about	10	59
Buff-weathering gray dolomite in thin beds, with intercalated intraformational conglomerate; forming terrace west of road in lot 9	11	49
Similar gray dolomite, having bed of *Cryptozoon* sp. cf. *C. undulatum* Bassler at top; exposed in terrace ascended by road	12	38
Unexposed	26	26
PRE-CAMBRIAN gneiss		
Exposed at and above river level in lot 9.		

glomeratic character of the Rockcliffe sandstone on Allumette Island implies that crystalline source rocks were near by in Chazyan time, and the absence of Canadian beds north of Lake Ontario requires the disappearance of the Beekmantown southward from the Renfrew area.

The thickness of the Beekmantown (March and Oxford formations) at Ottawa, where it lies on the Nepean sandstone, is given as 250 to 280 feet (A. E. Wilson, 1939); in the Arnprior district, the maximum thickness of the dolomite is about 30 feet (M. E. Wilson, 1924, p. 45), and it contains *Cryptozoön*. The beds thus thicken considerably to the east, probably by offlap, inasmuch as the basal dolomite in the western sections along the St. Lawrence is similar.

CHAZYAN SERIES

Rockcliffe formation.—The name Rockcliffe has been substituted (A. E. Wilson, 1937, p. 46) for the Aylmer shale and sandstone (M. E. Wilson, 1924, p. 48-50), the lower part of the Aylmer "formation" (Raymond,

1905, p. 380); the upper Aylmer beds are now classed as Pamelia (A. E. Wilson, 1932) and with the succeeding younger Black River and Trenton limestones have been placed in the Ottawa limestone (A. E. Wilson, 1937, p. 46).

The formation probably underlies each of the Paleozoic areas in Renfrew and Pontiac counties but because of its relatively low resistance it is rarely exposed. It is classified as Chazyan because it is overlain by the upper Chazyan St. Martin limestone east of Ottawa (A. E. Wilson, 1939). Chazyan rocks are lacking in the Lake Ontario homocline.

Rockcliffe sandstone occurs above the Beekmantown dolomite on Allumette Island. A good exposure of 8 feet of green and red shales with intercalated lensing and cross-laminated pebbly sandstone on the Bonnechere River half a mile above Douglas (lot 4, con. IX, Bromley) has beds like those of the Rockcliffe east of Arnprior; similar beds are exposed farther upstream (Murray, 1857, p. 96). The thickness in the area is not known, but from the breadth of outcrop between the pre-Cambrian and the Pamelia it is thought to be a few tens of feet. At Arnprior, there is 55 feet, and near Ottawa 140 to 150 feet.

MOHAWKIAN SERIES—BLACK RIVER GROUP

Classification.—The Mohawkian series is divided into two groups—the Black River and Trenton. In the type area the former comprises the Pamelia, Lowville, and Chaumont limestones. The first is a part of the original "Black River limestone" of Vanuxem (1842, p. 38) but was subsequently placed in the Chazyan (Cushing, 1910, p. 78-79) until it was shown that it overlies upper Chazyan in the Ottawa valley (A. E. Wilson, 1932). The name Chaumont was proposed (Kay, 1929, p. 664) because the Leray and Watertown limestones in the typical Black River were not recognizable laterally, except where separated by the Glenburnie shale; and the latter was then found to be at the base of the Chaumont rather than within it (Young, 1937) and to be a facies repeated at more than one horizon within the Chaumont. The "Leray" of Ontario has included beds of differing ages, and the problem will be more fully discussed with the Rockland formation, in which much of the Ontario "Leray" is included.

The three formations are represented both in the Ottawa valley and in southeastern Ontario.

Pamelia formation.—Two sections in Renfrew County display beds similar to those classified as Pamelia limestone at Ottawa (A. E. Wilson, 1934) and as Aylmer limestone at Arnprior (M. E. Wilson, 1924, p. 50).

Along the Bonnechere is a fairly continuous section below the bridge at Douglas. Thirty feet of dolomite and intercalated greenish and tan shale, dipping 12° eastward,

is exposed west of a concealed interval that would cover 10 feet of beds above the dam; below the dam, 20 feet of bedded dolomite is overlain by 4 feet of limestone forming the top of the cliff back of the mill; spheroidal structures resembling *Cryptozoön* are present in the dolomite just below the dam. Along the roadside west of the section are reddish shales with intercalated ostracode-bearing thin limestones. The individual beds in Murray's section (1857, p. 94-95) have not been recognized; he states that a fault crossed the section, which was made before the channel was flooded, but there is no duplication in the beds now exposed. The railroad cut through a faulted anticline east of Douglas Can. Pac. Ry. station exposes 27 feet of similar beds, the dolomite having intercalations of white and dark limestone containing leperditiid ostracodes. In summary, there is at least 60 feet of beds at Douglas. The lower portion is red and greenish shale and intercalated dolomites with thin interbeds containing ostracodes; the higher is dolomite, with spheroidal structures, and limestone. The rocks are similar to those described as Aylmer limestone at McLarens Landing, below Arnprior (M. E. Wilson, 1924, p. 51).

The other section of interest is on the east bank of the Ottawa River at Allumette Rapids, below Pembroke. Silty shales at river level are succeeded by 18 inches of quartz siltstone, overlain by 5 feet of calcareous claystone and dolomite; the upper dolomite bed has *Raphistoma distincta* Wilson in its base. Twenty feet higher are ledges of lower Lowville limestone. The thickness of the Pamelia seems to be about 20 to 30 feet at this locality.

It has been shown (A. E. Wilson, 1934) that the beds in the Ottawa district are like the Pamelia limestone of New York State. The formation lies directly on the pre-Cambrian north of Lake Ontario and has been described in the Kingston district (Baker, 1916, p. 40-42). The writer did not study the formation critically in the area to the west, but it has been surveyed by Young (1937), who reports a thickness of 30 feet at Marmora, Hastings County. The lowest Black River beds (Shadow Lake formation) east of Lake Simcoe may also be Pamelia in age (Okulitch, 1939, p. 325).

Lowville limestone.—In the Ottawa-Bonnechere graben there are a number of exposures of the Lowville formation, but the only full section seen is that in lot 37, South Bonnechere Range, 2 miles west of Northcote. The 50 feet of beds (Table 2) closely resembles the section in the Arnprior district at McLarens Landing (A. E. Wilson, 1921, p. 28), which has been measured by the writer for comparison (Table 3).

According to Raymond (1914b), *Cryptophragmus antiquatus*, originally described from the "Beatricea beds" (lower Gull River, Okulitch, 1939) of Central Ontario, is abundant in the uppermost Pamelia near Aylmer, present in the top bed of the Pamelia at Clayton, New York, and in and below the Lowville at Mechanicsville, near Ottawa; Young (1937) collected the species in the Lower Pamelia at Perch Lake, New York. The writer believes that the beds west of Northcote should be classified as

Lowville because they are associated with limestones like those in the higher Lowville.

Half a mile north of Allumette Rapids, limestone with *Strophomena* sp. and *Rhynchotrema* sp. is exposed about 20 feet above the Pamelia beds at the rapids,

TABLE 2.—*Section 2 miles west of Northcote, Ontario*

Formational description	Thickness in feet	
	of unit	to base of section
MOHAWKIAN series		
BLACK RIVER group		
CHAUMONT formation:		
Heavy ledge of dark, fine-textured limestone at the base; higher beds are exposed along the road westward, the upper, platy beds in front of the Town Hall.		
LOWVILLE formation:		
Platy, calcareous shale, exposed in cliff along roadside	2	45
Limestone and shaly limestone, only partially exposed; upper beds laminated and rippled	19	43
Argillaceous limestone, in field south of road	2	24
Gray, fine-textured limestone, with glauberite crystal impressions, and associated limestone with calcite casts of *Cyrtodonta* sp. abundant; exposed at base of hill along road and on crest of small knoll 100 yards to south	1	22
Calcareous shale and limestone, poorly exposed	13	21
Gray, fine-textured limestone and oölitic limestone with *Cyrtodonta* casts	2	8
Principally concealed	4	6
Heavy ledges of gray limestone, with associated impure limestone containing *Cryptophragmus antiquatus* Raymond, *s. l.*; and beds with *Cyrtodonta* casts	2	2

and a similar distance below glauberite-bearing limestone along the roadside half a mile northeast. Similar *Strophomena*-bearing lower Lowville is shown in a shallow quarry a mile north of the Allumette-Pembroke ferry pier. Fourteen feet of limestone and intercalated shale in the Pembroke city quarry, in the southeast part of the city (Goudge, 1938, Pl. 22A), contains *Bathyurus extans* Hall, *Fletcheria sinclairi* Okulitch, and *Strophomena* sp. and seems to be lower Lowville. In Meath Hill quarry, half a mile south of Meath station, calcareous shales like the uppermost beds at Northcote are exposed beneath the Chaumont. About 14 feet of dolomitic limestone with succeeding calcareous shale along Lake Doré in lot 8, con. XI, Wilberforce Township, is probably Lowville.

The Lowville formation in Renfrew County is very like that in southeastern Ontario. The most accessible section for comparison is that in the highway cut east of Napanee (Goudge, 1938, Pl. 2A), in which 49 feet of Lowville is exposed with the top 13 feet 3 inches below the 3-foot shale near the top of the cut, the higher beds being Chaumont limestone.

The contact is more accessible in a quarry east of the road southeast of the cut, where 3 feet of shaly Lowville with *Tetradium cellulosum* Hall in the upper 17-inch limestone ledge is overlain by a 16-inch ledge at the base

TABLE 3.—*Section at McLarens Landing, Carleton County*

Formational description	Thickness in feet	
	of unit	to base of formation
MOHAWKIAN series		
TRENTON group		
ROCKLAND formation:		
Gray, medium-textured limestone; exposed west of field at top of hill	4	.....
BLACK RIVER group		
CHAUMONT formation:		
Gray, thin-bedded, platy limestone, containing *Tetradium cellulosum* Hall	4	37
Concealed beneath field	7	33
Dark brown, dense, fine-textured limestone; at brow of hill above road	5	26
Concealed in slope	13	21
Brown, dense, heavy-ledged limestone	4	8
Gray, fine-textured limestone, containing *T. cellulosum* in abundance; along road; lithologically like Chaumont but may be Lowville	4	4
LOWVILLE formation:		
Concealed	20	49
Blue-gray limestone with some sublithographic white beds and shaly limestones	11	29
Gray, dense limestone with glauberite crystal impressions, and associated gray crystalline limestone with calcite casts of *Cyrtodonta* sp.	2	18
Shaly limestone, similar to that bearing *Cryptophragmus* west of Northcote; that genus was *not* found	6	16
Poorly exposed	10	10
PAMELIA limestone:		
Gray, medium to fine-textured limestone in heavy ledges, exposed along roadside	6	84
Concealed	18	78
Calcareous shale along terrace east of road	2	60
Gray, fine-textured, glauberite crystal impression bearing limestone; same beds that form top of 58 foot exposure between lake and road farther west.		

of the Chaumont containing *Gonioceras anceps* Hall. The formation has not been separately mapped by the writer in southeastern Ontario (Pl. 7) but has been studied by Young (1937). In both regions, somewhat oölitic beds with casts of *Cyrtodonta* sp. are abundant, particularly in the lower part of the formation, and glauberite crystal impressions are frequent.

Chaumont limestone.—The Chaumont limestone, excellently shown in the district, is quite uniform. The most complete sections are in the hill south of Meath station, Westmeath Township, and at the Fourth Chute of the Bonnechere River. In the former, the contact with the Lowville

TABLE 4.—*Section of Chaumont limestone south of Meath*

Description of formation	Thickness of unit (Ft.)	(In.)	Thickness to base of formation (Ft.)	(In.)
MOHAWKIAN series				
TRENTON group				
ROCKLAND limestone:				
Coarse-textured gray, tan-weathering limestone with *Columnaria halli* Nicholson, *Calopoecia canadensis* Billings, *Receptaculites occidentalis* Salter, and a large associated fauna (Table 8)	.....		.....	
BLACK RIVER group				
CHAUMONT limestone:				
Concealed	8		.....	
Gray, buff-weathering, platy limestone with intercalated tan shale containing *T. fibratum* Safford succeeded by 6-inch bed replete with *T. cellulosum* Hall, forming top of terrace	5	4	34	8
White, sublithographic limestone, exposed in highway cut, and forming terrace below higher beds east of the highway; surface of ledge 2 feet from top	6	4	29	4
Shaly limestone with two intercalated heavy ledges of dark-brown limestone, the upper with *T. cellulosum; T. fibratum* forming large heads in lower shales	8	0	23	0
Ledge of buff-weathering gray limestone prominent in top of quarry	1	7	15	0
Buff-weathering, blue, argillaceous limestone; richly fossiliferous (Table 5)	4	7	13	5
Two heavy ledges of dark, fine- to medium-textured limestone	7	10	8	10
Ledges of shaly limestone with *T. fibratum*	1	0	1	0
LOWVILLE limestone:				
Shaly limestone with *T. cellulosum*		10	.....	
Blue-gray, calcareous shale, containing *Bathyurus extans* Hall; exposed	4	0	.....	

is exposed, but that with the Rockland is concealed; in the latter, the base is beneath the river level.

The section in Meath Hill begins in the quarry east of the road half a mile south of the station and continues on the hillside to the north (Table 4; Pl. 3A). The thickness of the Chaumont in the section is between 35 and 40 feet.

At the Fourth Chute, the contact between the platy, *Tetradium fibratum*-bearing Chaumont and the coarse, siliceous Rockland is 7 feet 2 inches above the 4 feet of white, sublithographic limestone forming the conspicuous ledges in the falls; 37

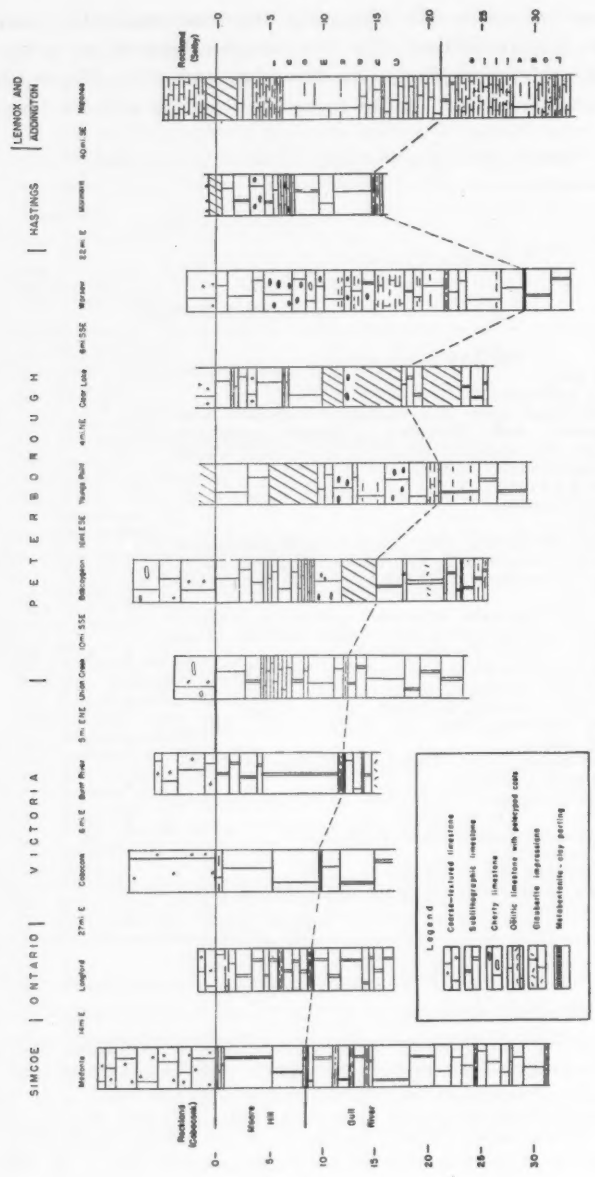


FIGURE 3.—*Sections of the Chaumont formation*
Between Lake Huron and Napanee, Ontario. Diagonal lines represent concealed intervals.

feet of Chaumont beds is exposed, the lowest containing *Columnaria halli* Nicholson, *Actinoceras* sp., and *Eospongia* (?) sp. The two upper members of the formation are consistently white limestone and platy gray, *T. fibratum*-bearing limestone. Their contact with the Rockland is exposed in the quarry of the Dominion Rock Products, Ltd., half a mile to the west, the uppermost platy member being 4 feet 3 inches thick,

TABLE 5.—*Faunule from the Chaumont limestone, quarry south of Meath station, Renfrew County*

Columnaria halli Nicholson
Fletcheria sinclairi Okulitch
Lichenaria typa Ulrich
Prismostylus columnaris (Hall)
Streptelasma corniculum Hall

Escharopora recta Hall
E. confluens Ulrich
Doleroides sp.
Glyptorthis bellarugosa (Conrad)
Rhynchotrema minnesotensis Sardeson
Strophomena sp. cf. *S. conradi* Hall and Clarke
S. sp. cf. *S. filitexta* (Hall)
Zygospira recurvirostris (Hall)

Clionychia sp. aff. *C. amygdulina* (Hall)
Cyrtodonta huronensis Billings
C. sp. cf. *C. rotundata* (Hall)
Helicotoma planulata Salter
Hormotoma gracilis (Hall)
Raphistomina sp. cf. *R. lapicida* (Salter)
Trochonema sp. cf. *T. umbilicata* (Hall)
Subulites sp.

Beloitoceras sp.
Ormoceras (?) sp.
Spyroceras sp.
Zitteloceras sp.

Bathyurus sp. aff. *B. ingalli* Raymond
Bumastus milleri Billings
Ceraurus pleurexanthemus (Hall)
Eoharpes sp.
Hemiarges sp. cf. *H. paulianus* (Clarke)
Illaenus sp.
Isotelus sp.
Thaleops ovata Conrad

Drepanella crassinoda Ulrich
Leperditia canadensis Jones

and along the Eganville-Cobden road in con. VII, Bromley Township, where 5 feet of the platy beds contains abundant large heads of *T. fibratum*.

The Chaumont limestone in Renfrew County is most like that in Hastings County, southeastern Ontario, where heavy ledges of dark limestone contain intercalated shaly beds and white sublithographic limestone. The formation is considerably thinner at Ottawa and has only the massive facies; the change takes place east of McLarens Landing (A. E. Wilson, 1921). The stratigraphy of the Chaumont of southeastern Ontario has been studied by Young (1937), who has traced the facies changes westward to Hastings County. The problems of the classification and correlation of the formation will be discussed with those of the Rockland.

MOHAWKIAN SERIES—TRENTON GROUP

Classification.—The classification of the Trenton Group has been discussed (Kay, 1937, p. 237-251; 1935, p. 582-586). In Ontario, the formations are the Rockland, Hull, Sherman Fall, Cobourg, Collingwood, and Gloucester. The Sherman Fall is separable into the Shoreham and Den-

mark members in New York; these are mappable formations southwest of the Adirondacks, and the Vermontian disturbance of the middle Trenton followed the deposition of the former. The Collingwood and Glouces-

TABLE 6.—*Species originally described from the Rockland limestone at Paquette Rapids, Allumette Island, Quebec*

Receptaculites occidentalis Salter
Calopoecia canadensis Billings
Columnaria halli Nicholson
C. magnifica Okulitch
Lambeophyllum apertum (Billings)
Paleoalveolites paquettensis Okulitch

Orthorhynchula ottawaensis (Billings)
Skenidioides billingsi Schuchert and Cooper

Ctenodonta abrupta Billings
C. astartaeformis Salter
C. contracta Salter
C. gibberula Salter
C. logani Salter
C. nasuta Salter
C. spinifera Billings
Conocardium immaturum Billings
Cyrtodonta leucothea Billings
Modiolopsis nais Bilings

Bellerophon charon Billings
Cyclonema halliana Salter
Eotomaria dryope (Billings)
Eunema cerithioides Billings
E. strigillata Salter
Gyronema semicarinatum (Salter)
Helicotoma larvata Salter
H. muricata Salter
H. planulata Salter
H. spinosa Salter
Holopea pyrene Billings
Hormotoma procris Billings
H. salteri Ulrich and Scofield

Liospira mundula Ulrich and Scofield
L. vitruvia (Billings)
Lophospira helicteres (Salter)
L. serrata (Salter)
Loxonema murrayana (Salter)
Maclurites logani (Salter)
Metoptoma erato Billings
Omospira alexandra (Billings)
Oxydiscus argo (Billings)
Raphistomina aperta (Salter)
R. lapicida (Salter)
Scenella superba (Billings)
Solenospira pagoda (Salter)
Straparollina asperostriata (Billings)
Straparollus circe Billings
S. eurydice Billings

Actinoceras billingsi Foerste
A. paquettensis Foerste
Allumettoceras tenerum (Billings)
Cyrtocerina typica (Billings)
Deiroceras paquettense Foerste
D. pertinax (Billings)
Kionoceras allumettense Foerste
K. paquettense Foerste
Loganoceras paquettense Foerste
L. regulare (Billings)
Ormoceras allumettense (Billings)
O. paquettense Foerste
Orthoceras ontarioensis Foerste
O. tener Billings
Paquettoceras allumettense Foerste
Richardsonoceras falx (Billings)
Spyroceras allumettense Foerste
S. paquettense Foerste
Tripteroceras hastatum (Billings)
T. paquettense Foerste
Zitteloceras billingsi (Salter)

Aparchites concinnus Jones
Cytheropsis siliqua Jones
Leperditia paquettiana Jones
Macronotella rugosa (Jones)
Chiton canadensis Billings

ter are believed equivalent to the Upper Utica (Holland Patent) of New York. All the formations of the Trenton Group are present in the Ottawa valley and in the Lake Ontario homocline, though the Collingwood is the youngest represented in the region of the present study.

Rockland limestone.—The Rockland limestone has been critically studied and mapped along the belt of outcrop from northwestern New York State to Georgian Bay, Ontario, as well as in the Renfrew County district; the areal distribution in southeastern Ontario and Renfrew

County is shown (Pls. 6, 7). There has been confusion and disagreement regarding the correlation of the upper Black River and lowest Trenton in New York and Ontario. The writer's conclusions have been summarized (Kay, 1937, p. 251-259) and will be discussed more fully.

The standard sections of the formations of the Black River Group are in northwestern New York State, those of the lower Trenton in the Ottawa district, Ontario. In New York, the uppermost Black River—the Chaumont formation—is separable into two members, the Leray and Watertown limestones, only in a limited area near Watertown. It is succeeded here, and in southeastern Ontario, by dark, shaly limestones containing *Doleroides*—the Selby member of the Rockland formation—and limestones bearing *Triplesia cuspidata* Hall in their upper beds—the Napanee member; faunas are listed in Tables 7 and 8.

The type section of the Rockland formation is east of Ottawa. It has been described (A. E. Wilson, 1921) as consisting of the "Leray," comprising 9 feet 6 inches of "Leray proper" and 8 feet 6 inches of "transition beds," overlain by 40 feet of Rockland limestone. The writer stated (Kay, 1937, p. 251) that the "Leray beds" at Rockland are post-Watertown; restudy of the section has convinced him that only the "transition beds" are post-Watertown, and that the 9 feet 6 inches of "Leray proper" is Chaumont, as was concluded by Raymond and by A. E. Wilson (1921). That the Rockland above the "transition beds" is equivalent to the Napanee is strongly suggested by the fauna (Table 8) and by the fact that each is overlain by limestones containing the Hull crinoid fauna (Raymond, 1914a, p. 348). The lithology, as well as the fauna, of the "transition beds" resembles that of the Selby member of the Rockland, which is post-Chaumont.

In southeastern Ontario, the best continuous section from the heavy-ledged, coarse-textured Rockland limestone into the shaly Hull is that in the Can. Nat. Ry. cut east of Shannonville station, where 20 feet of Rockland is exposed beneath about 60 feet of Hull in the axis of a syncline.

In central Ontario, the Coboconk limestone was originally classified as "Leray" (Johnston, 1911, p. 189) and described as 35 feet thick south of Dalrymple. At Coboconk, white, sublithographic limestone (Gull River of Okulitch, 1939) is succeeded by 12 feet of Moore Hill limestone and 21 feet of Coboconk limestone to the top of the exposure in the quarries. The writer (Kay, 1937, p. 256) classified the Moore Hill as Chaumont and the Coboconk as Rockland-Napanee, but Okulitch (1939, p. 339) states that he is "convinced that the Coboconk should remain in the Black River group" and places the Moore Hill in the Lowville. The writer's conclusion that the Coboconk is Rockland in age was based on the fact that the fauna of the upper beds at Dalrymple is quite like that of the type Napanee, many of the species are present to the base of the formation at Coboconk, and the Moore Hill limestone, beneath, seems continuous eastward into the type Chaumont. The fauna at Dalrymple is listed (Table 8).

Only the lower 20 feet of the Coboconk is exposed in the quarries at the village of Coboconk; Okulitch recognized that the upper 13 feet of this "may conceivably" be Rockland, but he lists from the lower beds *Bellerophon charon* Billings, *Holopea nereis* Billings, and *Hormoceras tenuifilum* (Hall) as "typical Black River forms", though they are in Johnson's list for the higher beds at Dalrymple, and two were originally described from the Paquette Rapids Rockland (Table 6). The writer (Kay, 1931, p. 369) was impressed also at one time by the Black River aspect of some of the species. In explanation of Okulitch's observation that neither *Doleroides ottawanus* (Wilson) nor *Triplesia cuspidata* (Hall) is present in the Coboconk at the village, the Selby member of the Rockland, characterized by the former (Table 7), is overlapped west of Lennox and Addington County by the Napanee member, and

TABLE 7.—*Faunules from the Selby member of the Rockland formation*

	Localities		
	1	2	3
Batostoma sp.	.....	c	.....
Eridotrypa sp.	.....	.....	u
Mesotrypa sp.	.....	c	c
Prasopora insularis Ulrich	.....	.....	f
Pachydictya sp.	u	.....	.....
Rhynidictya sp.	.....	.....	f
Dalmanella sp. cf. *D. rogata* (Sardeson)	u	.....	f
Doleroides ottawanus Wilson	a	a	c
D. pervetus (Conrad)	.....	f	.....
Hesperorthis tricenaria (Conrad)	.....	f	.....
Rafinesquina sp.	u	u	u
Rhynchotrema sp.	u	u	.....
Strophomena sp.	c	c	.....
Ambonychia sp.	r	.....	.....
Ctenodonta gibberula Salter	.....	c	f
Cyrtodonta sp.	u	u	c
Endodesma sp. cf. *E. gesneri* (Billings)	u	r	f
Modiolopsis subtruncata (Hall)	u	.....	.....
Tellinomya nasuta Hall	.....	c	.....
Whitella sp.	.....	u	.....
Bellerophon (?) sp.	.....	u	u
Bucania intexta Hall	f	f	c
Carinaropsis sp.	.....	r	.....
Eotomaria supracingulata (Billings)	.....	u	.....
Helicotoma planulata Salter	f	c	.....
Holopea sp. cf. *H. nereis* Billings	.....	.....	u
Hormotoma bellicincta (Hall)	a	.....	.....
H. gracilis (Hall)	.....	c	c
Liospira vitruvia Billings	c	a	c
Lophospira perangulata (Hall)	f	a	u
Raphistomina lapicida (Salter)	u	c	c
Salpingostoma sp.	u	u	f
Scenella sp.	.....	r	r
Subulites sp.	f	c	u

TABLE 7.—*Faunules from the Selby Member of the Rockland formation*—Continued

	Localities		
	1	2	3
Allumettoceras tenerum (Billings)	f	u	.....
Beloitoceras sp	f	.....	.....
Cameroceras sp	.....	u	.....
Deiroceras pertinax (Billings)	.....	r	.....
Oncoceras collinsi Foerste	c	f	.....
Sactoceras sp	.....	a	.....
Spyroceras arcuoliratum (Hall)	.....	c	.....
S. bilineatum (Hall)	.....	a	.....
S. paquettense Foerste	f	f	.....
S. sp	.....	c	.....
Tripteroceras hastatum (Billings)	u	f	.....
T. sp	.....	u	.....
Bumastus trentonensis (Emmons)	.....	c	.....
Calymene senaria Hall	.....	.....	r
Ceraurus pleurexanthemus (Hall)	.....	f	f
Eomonorachos sp. cf. *E. eboraceus* (Walcott)	.....	f	.....
Illaenus sp	.....	r	.....
Isotelus sp	u	.....	u

Localities: 1—Selby Creek, type section of the Selby member, 1 mile north of Napanee, Ontario, in lot 23, con. III, Richmond Township, Lennox and Addington County;
2—South of road corner 1 mile west of Violet, in lot 10, con. V, Ernestown Township, Lennox and Addington County, Ontario;
3—Quarry 1 mile east of Dexter, Jefferson County, New York.
a = abundant, c = common, f = frequent, u = uncommon, r = rare, x = present.

T. cuspidata is found in the upper Napanee, in beds younger than those in the Coboconk quarries, but represented in the highest Coboconk south of Dalrymple.

With respect to the continuity of the Moore Hill eastward into the Chaumont (Fig. 3), the beds from Lake Huron to Burnt River are preponderantly fine-textured white or tan limestone, typical Moore Hill; there is a persistent metabentonite at the base. Black chert becomes common about Bobcaygeon, where the belt of outcrop is offset 10 miles southward, the beds thicken, and there is a persistent metabentonite beneath glauberite-bearing beds in the underlying Lowville. That *Tetradium cellulosum* Hall is not a guide to the Lowville is established (Okulitch, 1935, p. 56). In southeastern Ontario, the writer has not found *Columnaria halli* Nicholson below the Chaumont, where it is frequent, but the form is abundant in the Rockland and has been found in New York in the Hull and Sherman Fall. *Tetradium fibratum* Safford, rare in the Lowville, is frequent in the Chaumont and has been seen higher only in a rolled specimen from the type section of the Napanee (Table 8).

In Renfrew County, the most complete section of the Rockland is that in the Dominion Lime quarry west of Fourth Chute (Kay, 1937, p. 252; Goudge, 1938, p. 166). The basal beds are coarse-textured calcite sandstone, containing *Stromatocerium rugosum* Hall, *Receptaculites occidentalis* Salter, and *Columnaria halli* Nicholson, and lie directly on the platy, *Tetradium fibratum*-bearing upper Chaumont limestone. The exposed thickness of 53 feet consists principally of blue-gray, buff-weathering

TABLE 8.—*Faunules from the Rockland formation*

	1	2	3	4	5	6	7	8	9	10	11	12
Stromatocerium rugosum Hall	x	.	x	.	.	x	x	x	x	x	.	.
Receptaculites occidentalis Salter	c	x	T	x	W	x	x	x	.	x	.	.
Calopoecia canadensis Billings	f	.	T	x	.	x	x	x	.	x	.	.
Columnaria halli Nicholson	c	.	T	x	.	x	x	x	x	x	.	.
Lambeophyllum apertum (Billings)	c	.	T	.	.	.	.	.	.	.	x	.
Lichenaria coboconkensis Okulitch	.	.	.	.	.	.	.	.	x	x	.	.
Paleoalveolites paquettensis Okulitch	.	.	T	x	.	.	.	.	.	.	.	.
Streptelasma corniculum Hall	x	.	x	.	.	x	.	.	.	.	.	.
**Tetradium fibratum* Safford	.	.	.	.	.	.	.	.	.	*	.	.
Graptodictya flabellata (Hall)	.	.	.	.	.	.	.	.	x	.	.	.
Other bryozoans not listed												
Camarella volborthi Billings	c	x	.	.	.	.	.	.	.	.	.	.
Dalmanella rogata (Sardeson)	f	x	x	.	.	x	x	.	x	a	x	x
Doleroides pervetus (Conrad)	u	.	.	.	.	x	.	.	.	.	.	.
Glyptorthis bellarugosa (Conrad)	u	.	.	.	.	x	.	.	.	.	.	.
Hallina (?) sp.	r	.	.	.	.	.	.	.	.	.	.	.
Hesperorthis tricenaria (Conrad)	f	x	x	x	W	x	.	x	.	.	x	.
Leptaena sp. cf. L. *charlottae* Winchell and Schuchert	.	.	.	.	.	.	x	.	.	.	.	.
Parastrophina hemiplicata (Hall)	.	.	.	.	x	.	x	.	.	x	.	.
Dinorthis sweeneyi (Winchell)	c	.	.	.	.	.	.	.	.	.	.	.
Rafinesquina alternata (Conrad)	f	x	.	.	x	x	x	.	x	x	x	.
R. sp.	.	.	.	.	.	.	.	.	.	x	x	x
"Rafinesquina" inquassa (Sardeson)	f	x	.	.	x	x	x	.	x	x	x	.
Rhynchotrema increbescens (Hall)	f	x	.	.	.	x	.	.	.	.	.	.
Sowerbyella punctostriata (Mather)	u	x	x	.	.	x	.	x	x	a	x	.
Strophomena filitexta (Hall)	f	x	x	x	W	x	x	x	.	x	x	.
S. sp. cf. *S. conradi* Hall and Clarke	.	.	.	x	.	.	x	.	.	.	.	x
S. sp. cf. *S. emaciata* Winchell and Schuchert.	r	.	.	.	.	f	.	.	.	.	.	.
Triplesia cuspidata (Hall)	.	.	.	.	x	r	x	x	x	r	x	.
Zygospira recurvirostris (Hall)	.	x	.	.	.	x	.	.	.	.	.	x
Clionychia lamellosa (Hall)	.	.	x	.	.	.	.	.	.	.	.	.
Ctenodonta contracta Salter	.	.	T	x	.	.	.	.	.	.	.	.
C. logani Salter	.	.	T	.	.	.	.	.	.	x	.	.
Cyrtodonta sp. aff. *C. ampla* Ulrich and Scofield	.	.	x	.	.	.	.	x	.	.	x	.
C. sp. cf. *C. glabella* Ulrich and Scofield	.	.	.	.	.	.	.	.	.	x	.	.
C. sp. cf. *C. rotulata* Ulrich and Scofield	.	.	.	.	.	.	.	.	.	x	.	.
Sphenolium sp. aff. *S. parallelum* Ulrich and Scofield	.	x	.	.	.	.	.	.	.	.	.	.
Tellinomya nasuta Conrad	.	x	x	x	.	.	.	.	.	.	.	.
Whitella ventricosa (Hall)	.	.	.	.	.	.	.	.	.	x	x	.
Archinacella sp. cf. *A. valida* (Sardeson)	.	.	x	.	.	.	.	.	.	.	.	.
Bucania sp.	.	.	.	.	.	x	.	.	.	.	.	.
Carinaropsis sp.	.	.	.	.	.	.	.	.	.	.	.	x
Cyclonema halliana (Salter)	.	x	T	.	.	.	.	.	.	.	.	.
C. (?) sp.	r	.	x	.	.	.	.	.	.	.	.	.
Eotomaria dryope (Billings)	.	.	.	x	.	x	.	.	.	.	.	.
E. supracingulata (Billings)	r	.	.	.	.	x	.	.	.	.	.	.
Eunema strigillata Salter	.	.	T	x	.	.	.	.	.	.	.	.
Helicotoma planulata Salter	.	x	T	.	.	.	.	.	.	.	.	.
Holopea nereis (?) Billings	.	.	x	.	.	x	.	.	.	.	x	.
Hormotoma canadensis Ulrich and Scofield	f	x	x	x	x	R	.	.	.	.	.	.
H. bellicincta (Hall)	.	.	.	.	.	x	x	.	x	.	x	.
H. sp. cf. *H. procris* (Billings)	.	.	x	.	.	.	.	.	.	.	.	.
Liospira americana Billings	.	.	.	.	.	x	.	.	.	.	.	.
L. vitruvia Billings	.	x	x	.	x	x	.	.	.	.	.	x
Lophospira perangulata (Hall)	.	.	x	.	.	x	.	.	.	.	.	.
Maclurites logani (Salter)	c	.	T	x	x	R	x	x	x	x	.	.

TABLE 8.—*Faunules from the Rockland formation*—Continued

	1	2	3	4	5	6	7	8	9	10	11	12
Omospira alexandra (Billings)	f	.	x	.	.	.	.	.	.	.	.	.
Oxydiscus sp. cf. *O. disculus* (Billings)	c	.	T	.	.	.	.	.	.	.	.	.
Phragmolites compressus Conrad	f	.	.	x	x	.	.	.	x	x	x	.
Platyceras (?) *wisconsinensis* Ulrich and Scofield	.	x	.	.	.	.	.	.	.	.	.	.
Raphistomina lapicida (Salter)	f	.	T	x	.	x	.	.	.	.	.	.
Salpingostoma sp	f	x	.	.	.	.	.	.	x	.	.	.
Sinuites sp	.	.	.	.	.	.	.	.	.	.	.	x
Subulites sp	x	.	.	.	.	x	x	.	x	.	.	.
Tetranoda bidorsata (Emmons)	.	.	x	.	.	.	.	.	.	.	.	.
Trochonema canadensis Ulrich and Scofield	.	x	x	.	.	.	.	.	.	.	.	.
T. helicteres (Salter)	.	x	T	.	.	.	.	.	.	.	.	.
T. sp	x	.	.	.	.	.	.	.	.	.	.	.
Conularia sp	.	.	.	.	.	x	.	.	.	.	.	.
Pterotheca sp	.	x	.	.	.	.	.	.	.	.	.	.
Actinoceras bigsbyi Bronn	x	.	.	.	.	.	x	x	.	.	.	.
Centrocyrtoceras sp	.	x	.	x	.	.	.	.	.	.	.	.
Deiroceras pertinax (Billings)	x	.	T	.	.	.	.	.	.	.	.	.
Endoceras sp	x	.	.	.	.	.	.	.	.	.	.	.
Geisonoceras sp	.	.	.	.	.	.	.	.	.	.	.	x
Gonioceras sp. cf. *G. kayi* Foerste	c	.	x	.	.	.	.	.	.	.	.	.
Loganoceras regulare (Billings)	.	.	x	.	.	x	.	.	.	.	.	.
Maelonoceras billingsi Foerste	T	.	.	.	.	.	.	.	.	.	.	.
Paquettoceras allumettense Foerste	.	x	T	.	.	.	.	.	.	.	.	.
Richardsonoceras simplex (Billings)	x	.	.	.	.	.	.	.	.	.	.	.
Sactoceras sp	.	.	x	.	.	.	.	.	.	.	.	.
Spyroceras allumettense Foerste	.	x	T	x	.	.	.	.	.	.	.	.
S. bilineatum (Hall)	.	.	x	.	.	.	.	.	.	x	.	.
Tripteroceras sp	.	.	.	x	.	.	.	.	.	x	.	.
Zitteloceras billingsi (Salter)	.	.	.	x	.	.	.	.	.	.	.	.
Bathyurus spiniger (Hall)	f	.	x	x	.	x	x	.	.	x	.	.
Bumastus milleri (Billings)	f	x	.	x	W	x	.	.	x	x	x	.
Calymene senaria Hall	.	.	.	.	.	.	.	.	.	.	x	.
Ceraurinus trentonensis Barton	L	.	.	.	.	.	.	.	.	.	.	.
Encrinurus sp. cf. *E. cybeleformis* Raymond	.	.	.	.	.	.	.	.	x	x	.	.
Goldius lunatus (Billings)	.	.	.	.	.	.	.	.	.	.	x	.
Illaenus americanus Conrad	.	.	.	.	.	.	.	.	.	.	x	.
Calliops callicephalus (Hall)	u	.	.	.	.	x	.	.	.	.	.	.
Isotelus sp	.	.	.	.	.	.	.	.	x	.	.	.
Thaleops ovatus Conrad	L	x	.	x	x	x	x	.	.	.	.	.
Leperditia fabulites Conrad	L	.	.	.	.	.	.	.	.	.	.	.
Echinoderms not listed												

Localities: 1. Great Cloche Island, type section of Cloche Island formation, Manitoulin District;
2. 3 miles northeast of Deux Rivieres, Ontario, along highway; drift block;
3. Paquette Rapids, Allumette Island, Quebec; other species in Table 6;
4. Hill south of Meath station, Ontario;
5. Stewart quarry, near Rockland, Ontario; type section, Rockland formation;
6. One mile south of Dalrymple, Ontario, originally referred to section of Coboconk formation;
7. Lot 6, con. X, Carden Township, Victoria County;
8. Healey Falls, Ontario; ledges along river below falls;
9. 2 miles east of Shannonville, Ontario, quarry north of highway;
10. Selby Creek, north of Napanee, Ontario; type section of Napanee member;
11. Gretna, Ontario; terrace in village and quarry a mile to the west;
12. Northwest of Bath, Ontario, particularly quarry in lot 12, con. II, Ernestown Township.

a = abundant; c = common; f = frequent; u = uncommon; r = rare; x = present; L = from lower beds at east end of island; R = list of Raymond in Johnston, 1911; T = type locality; W = list of Wilson, 1921; * = specimen a pebble in place.

limestone with a few shaly interbeds. *Gonioceras* sp. cf. *G. kayi* Foerste is present in the uppermost beds, which are also well displayed in the Shane quarry south of Fourth Chute station (Goudge, 1938, p. 165). There are extensive exposures in the Renfrew County outliers (Pl. 6). Locally, the beds are dolomitized, the two carbonates being interbedded in the hillside 2 miles west of Douglas, and massive dolomite forming cliffs at the mill dam below Eganville.

The fauna of the formation is very large. More than 70 species have been described from Paquette Rapids alone (Table 6) where they are associated with *Dalmanella* sp. cf. *D. rogata* (Sardeson), *Hesperorthis tricenaria* (Conrad), *Sowerbyella punctostriata* (Mather), *Gonioceras* sp., and additional species (Table 8); the larger list of Ami (Ells, 1907, p. 60) is subject to some revision. In the past, the fossils described from Paquette Rapids have been referred often to the Black River or "Leray"; the similarity of the fauna to that in the Rockland, Napanee, Coboconk, and Cloche Island limestones is marked (Table 8), and the beds are of higher Rockland age.

Hull limestone.—The Hull formation is exposed extensively in the area north of Lake Ontario, and limitedly in Renfrew County. Though there is no continuous section in the latter district, the sequence can be compiled near Eganville (Table 9) and is about 60 feet thick.

The beds resemble more closely those of the Hull in the type section in the Ottawa district than those in southeastern Ontario, but there are significant faunal similarities with the latter (Table 10).

In the Lake Ontario homocline, Hull exposures are extensive along the Moira River from Latta to the Bay of Quinte, in the Can. Nat. Ry. cut east of Shannonville where the contact with the Rockland is exposed, in the eastern half of Amherst Island, and along the channel north of Amherst Island from west of Bath to east of Sandhurst, where the Hull is succeeded by the *Cryptolithus*-bearing basal Sherman Fall beds (Pl. 7). There is a total of about 100 feet, 85 feet being exposed in a vertical section between the Rockland and Sherman Fall in the cliff below Healey Falls, Northumberland County. In the large quarry at Kirkfield, Victoria County, Hull is overlain by the Sherman Fall.

Sherman Fall limestone.—The Sherman Fall formation is exposed at three separated areas within the Renfrew County district and extensively along Lake Ontario. In the former area, there are outcrops in lot 20, con. IX, Sebastopol Township, south of Lake Clear (Pl. 3B); in the Esmonde outlier, 2 miles east of Lake Clear; and at Jessups Rapids power dam, a mile below Eganville on the Bonnechere River (Fig. 4). It is probably about 75 feet thick, as evidenced by the stratigraphic in-

terval concealed between the Sherman Fall and lowest Cobourg exposures at Lake Clear. The formation is about 200 feet thick along Lake Ontario, and the beds in the Ottawa Valley are believed to represent only the lower part of the whole formation. The overlying Cobourg formation is discon-

TABLE 9.—*Section of the Hull limestone at Eganville*

Formational description	Thickness in feet	
	of unit	to base of formation
MOHAWKIAN series		
TRENTON group		
HULL limestone:		
Gray, buff-weathering, heavy-ledged dolomite forming bluff south of the Bonnechere River in Eganville, and island within the river at rapids; exposed, about.....	35	69
Gray limestone and dolomite in platy beds, with silicified fossils and gray chert; in south channel of river at Eganville Rapids, in small quarry east of corner by Lutheran Church, and north of road south of river above grist mill bridge; fauna in Table 10; about.....	8	34
Calcareous shale and shaly limestone; in quarry east of Lutheran Church.....	8	26
Gray limestone with shaly partings (5′), overlying calcareous shale with abundant fossils (Table 10), (5′) and limestone like that above (3′) in quarry south of Lutheran Church.....	13	18
Gray, coarse-textured, massive ledge of limestone in lower part of quarry south of church, and in small quarry to the east of the road; may belong in Rockland formation.....	5	5
ROCKLAND formation:		
Brown, sugary dolomite with strophomenid brachiopod molds, becoming limestone laterally; east of road northwest of grist mill.....	16	
Brown dolomite and gray limestone in heavy ledges.....		

formable upon it. The thickness at Ottawa is about 25 feet (A. E. Wilson, 1936, p. 9).

The exposures at Lake Clear disclose 5 feet of shaly limestone and intercalated shale. At Esmonde, 30 feet of platy gray limestone with shaly interbeds in a small quarry and ravine in lot 30, con. VII, Grattan, is separated by a concealed stratigraphic interval of about 100 feet from the top of the Rockland limestone a quarter of a mile to the west. At Jessups Rapids, the gently west dipping limestones have interbeds of shale and are isolated by faulting and drift cover from other formations. The faunules from the localities are given in Table 11.

In southeastern Ontario, the formation is extensively exposed in Prince Edward County, in western Amherst Island, and along the north shore of Adolphustown Reach (Pl. 7). There are also limited exposures west of the Moira River, where drift cover is extensive. *Cryptolithus tesselatus* Green is present with *Prasopora orientalis* Ulrich

TABLE 10.—*Faunules from the Hull formation in Ontario*

	Localities							
	1	2	3	4	5	6	7	8
Camarocladia sp.					x			
Columnaria halli Nicholson			x					
Lambeophyllum profundum (Hall)			x	x			x	x
Lichenaria sp.					x			
Streptelasma corniculum Hall			x	x			x	x
Atactoporella sp.					x			
Chasmatopora sublaxa (Ulrich)					x		x	x
Escharopora confluens Ulrich			x		x			
E. subrecta Hall					x		x	
E. n. sp.					x			
Eridotrypa mutabilis Ulrich					x	x	x	x
Pachydictya acuta Hall					x		x	x
Prasopora insularis Ulrich		x	x			x	x	x
Rhinidictya mutabilis Ulrich					x	x	x	x
R. paupera Ulrich						x		x
R. trentonensis Ulrich					x		x	
Trigonodictya conciliatrix Ulrich					x		x	
Dalmanella rogata (Sardeson)		x	x	x	x	x	x	x
D. sp.	x							
Dinorthis sweeneyi (Winchell)		x			x		x	
D. (*Plaesiomys*) *meedsi* Winchell and Schuchert	x							
Doleroides pervetus (Conrad)			x		x	x	x	
Glyptorthis bellarugosa (Conrad)	x							
Hesperorthis tricenaria (Conrad)		x		x	x	x	x	x
Parastrophina hemiplicata (Hall)					x		x	
Platystrophia trentonensis McEwan		x			x	x		
Rafinesquina trentonensis (Hall)	x	x	x		x	x	x	x
"*Rafinesquina*" *inquassa* (Sardeson)		x		x				x
"*R.*" *wagneri* (Okulitch)					x	x		
Rhynchotrema increbescens (Hall)	x	x	x	x	x	x		
Schizambon sp.			x					
Skenidioides anthonense (Sardeson)						x		
Strophomena filitexta (Hall)		x	x	x	x	x	x	x
S. sp. cf. *S. conradi* (Hall and Clarke)		x						
S. sp.				x				
Zygospira recurvirostris (Hall)		x			x	x		
Endodesma gesneri (Billings)							x	
Saffordella modesta Ulrich					x			
Archinacella simulatrix Ulrich and Scofield				x				
Bucania intexta Hall					x	x	x	x
Carinaropsis acuta Ulrich and Scofield							x	x
Cyclonema montrealense Billings					x		x	x
Helicotoma planulata Salter				x				
Holopea symmetrica Hall							x	x
Hormotoma gracilis (Hall)				x			x	
Liospira angustata Ulrich and Scofield						x		
L. vitruvia Billings				x	x	x	x	x
Lophospira bicincta (Hall)					x		x	x
Omospira alexandra (Billings)				x	x		x	x
Phragmolites compressus Conrad				x			x	x

TABLE 10.—*Faunules from the Hull formation in Ontario*—Continued

	Location							
	1	2	3	4	5	6	7	8
Raphistomina lapicida (Salter)				x	x			x
Scenella sp. cf. *S. compressa* Ulrich and Scofield								x
Tetranota bidorsata Emmons								x
Trochonema sp.				x	x			
Sinuites cancellatus Hall				x	x			
Hyolithes sp. cf. *H. pinniformis* Ruedemann							x	x
Cameroceras sp.		x						
Cycloceras sp. cf. *C. decrescens* (Billings)	x							x
Ehlersoceras (?) sp.			x					
Beloitoceras sp.					x		x	
Tripteroceras planoconvexum (Hall)					x			
Spyroceras arcuoliratum (Hall)							x	x
S. bilineatum (Hall)			x					
Bathyurus ingalli Raymond				x		x		
Bumastus milleri (Billings)						x	x	
Calymene senaria Hall						x	x	
Calliops callicephalus (Hall)	x				x	x	x	x
Ceraurus sp.	x		x	x	x	x	x	x
Encrinurus cybeleformis Raymond		x	x			x	x	x
Goldius lunatus (Billings)					x			
Hemiarges paulianus (Clarke)			x		x	x		x
Isotelus gigas Dekay	x						x	
Thaleops ovatus Conrad		x		x				
Leperditia fabulites Conrad				x				
Echinoderms not listed								

Localities: 1. Eganville; limestone in rapids in village. 2. Eganville; shales in quarry south of Lutheran church. 3. Belleville; limestones along Moira River. 4. 2 miles east of Belleville; limestones in quarry adjoining highway at power-line crossing. 5. Shannonville; from 60 feet of exposed beds along Can. Nat. Ry. 6. ⅝ mile east Mount Pleasant School; in drainage ditch. 7. East of Sandhurst; long exposure along Lake Ontario. 8. Amherst Island; northeast and southeast shores, mollusks principally from single bed in latter area.

in limestones about 30 feet above the base of the formation along the lake shore in lot 14, con. I, Fredericksburgh South; this is the only locality in Ontario at which *Cryptolithus*, characteristic of the basal Sherman Fall, has been collected by the writer. Basal Sherman Fall limestone with abundant *P. orientalis* is exposed at many localities (Pl. 7), as along the west slope of the Ameliasburg inlier and in the quarries a mile west of Canniston. Farther west, the beds form the top of the bluff east of Healey Falls, Northumberland County, and the upper part of the Kirkfield Crushed Stone quarry in Victoria County. The thickness of the formation in northwestern New York and southeastern Ontario is about 200 feet.

Cobourg limestone.—In Renfrew County, the only outcrop of the Cobourg formation is in the outlier south of Lake Clear; the beds are ex-

tensively exposed in Prince Edward County in southeastern Ontario. South of Lake Clear, an excellent section of 114 feet of sediments is exposed along Falls Creek, in lot 21, con. IX, Sebastopol Township (Pl. 3B); *see* Table 12.

TABLE 11.—*Faunules from Sherman Fall formation, Renfrew County, Ontario*

	Loc. 1	Loc. 2		Loc. 1	Loc. 2
Prasopora orientalis Ulrich	x	x	*Vellamo trentonensis* Raymond	x	x
Homotrypa sp.	x	.	*Zygospira recurvirostris* (Hall)	x	x
Eridotrypa sp.	x	.	*Cyrtodonta* sp. cf. *C. glabella* Ulrich	.	x
Dalmanella sp. cf. *D. rogata* (Sardeson)	x	x	*Whitella* sp. cf. *W. ventricosa* (Hall)	.	x
Dinorthis sweeneyi (Winchell)	.	x	*Hormotoma* sp. cf. *H. trentonensis* (Hall)	x	x
D. (Plaesiomys) meedsi Winchell and Schuchert	x	.	*H. gracilis* (Hall)	.	x
Pholidops trentonensis Hall	x	.	*Bucania* sp.	.	x
Platystrophia extensa MacEwan	x	.	*Oxydiscus* sp.	.	x
Pseudolingula sp.	x	.	*Calliops callicephalus* (Hall)	.	x
Rafinesquina praecursor Raymond	x	x	*Calymene senari* (Hall)	.	x
Rhynchotrema increbescens (Hall)	x	x			
Strophomena sp. cf. *S. emaciata* Winchell and Schuchert	x	.			

Localities: 1. Jessups Rapids, 1 mile east of Eganville. 2. Edmonde outlier, west of Edmonde.

Along the road to the west, Sherman Fall shaly limestone is exposed about 20 feet above the lake at the road corner; following a concealed stratigraphic interval of about 45 feet is 18 feet of coarse-textured, crystalline limestone. The concealed interval to the Collingwood exposures 75 feet higher and 1200 feet to the southeast is about 150 feet. The coarse-textured beds are thought to be lowest Cobourg, to lie disconformably on the Sherman Fall, and beneath the beds exposed on Falls Creek. The total thickness of the Cobourg is thus estimated at 140 to 150 feet, of which nearly the whole is shown in the two exposures.

The beds along Falls Creek are in their upper part faunally and lithologically like the Upper Cobourg (Hillier member) of northwestern New York (Kay, 1933) and southeastern Ontario (Kay, 1937, p. 280); the subjacent beds are faunally like the Lower Cobourg (Hallowell member), though not so heavy-ledged. The lowest exposed beds are probably the equivalent of the Cystid beds at Ottawa, originally placed in the Sherman Fall (Raymond, 1914, p. 346), more recently in the Cobourg (A. E. Wilson, 1936, p. 10); the latter designation is supported by the fact that they seem to succeed coarsely crystalline limestones that are thought to overlie the Sherman Fall disconformably. The total thickness is but little less than the estimated 170 to 200 feet in southeastern Ontario (Kay, 1937; Sproule, 1936). The stratigraphy and fauna in the latter

area have been discussed by Sproule (1936), and the distribution is shown on Plate 7.

Collingwood shale.—The Collingwood shale is exposed only in the outlier south of Lake Clear in Renfrew County; in southeastern On-

TABLE 12.—*Section south of Lake Clear*

Description of formation	Thickness in feet	
	Of unit	To base of exposure
MOHAWKIAN series		
TRENTON group		
COBOURG limestone:		
Shaly limestone, exposed interruptedly along Falls Creek above falls and rapids; probably approaching base of Collingwood shale	30	114
Argillaceous limestone with intercalations of gray, medium-textured, granular limestone with *Sowerbyella semiovalis* Wilson, *Leptelloidea gibbosa* (Winchell and Schuchert), *Cyclospira bisulcata* (Hall), and *Rafinesquina* sp.: Upper Cobourg	36	84
Gray, medium to coarse-textured limestone, with shale partings; having *Rafinesquina deltoidea* (Conrad) and *Hormotoma trentonensis* Ulrich and Scofield: Lower Cobourg	30	48
Gray, medium-textured limestone with intraformational conglomerate, a bed near the base containing *Vellamo trentonensis* Raymond and *Pleurocystites* sp.; probably corresponding to the "Cystid beds" at Ottawa; to base of exposure	22	22
Concealed to the lake	37	

tario, the belt of outcrop lies beneath Lake Ontario. South of Lake Clear, there is an excellent exposure of black shale with thin intercalated limestones representing the transition to the underlying Cobourg, along the stream south of the southwest corner of the lake in lot 20, con. XI, Sebastopol; the shales are exposed along the roadside in lot 16, con. IX, half a mile to the east (Pl. 3B). The exposed beds are about 20 feet thick, and the fauna (Table 13) is clearly that of the Collingwood shale of the Ottawa district and central Ontario (Parks, 1929).

PLEISTOCENE DEPOSITS

Although Pleistocene sediments are widespread in both Renfrew County and southeastern Ontario, their presence is more significant to the bedrock study in the former area. In the Ottawa valley, the marine Champlain clays and sands attain an elevation of nearly 700 feet in the vicinity

of Ottawa (Johnston, 1917, p. 18-24). Westward in the area of Paleozoic outliers, the deposits mantle nearly the whole of the bedrock at lower elevations, so that the mapping of the submantle outcrops is in many areas quite impracticable. Sand and clay plains are quite continuous to elevations of 700 feet in the Bonnechere and Ottawa valleys, and, inasmuch as most of the preserved Paleozoic lies below this elevation, its

TABLE 13.—*Collingwood faunule, Lake Clear*

Climacograptus typicalis Hall	f	*Sowerbyella* sp.	c
Lingula sp.	c	*Geisonoceras tenuistriatum* (Hall)	c
Dalmanella sp. cf. *D. emacerata* (Hall)	c	*Ogygites latimarginatus* (Hall)	a
Rafinesquina camerata Raymond, not (Conrad)	c	*Triarthrus eatoni* Hall	c

a = abundant; c = common; f = frequent.

exposures are of limited extent. The pre-Cambrian rocks are well exposed on the higher scarps (Pl. 1), though in some areas till covers the rock surface.

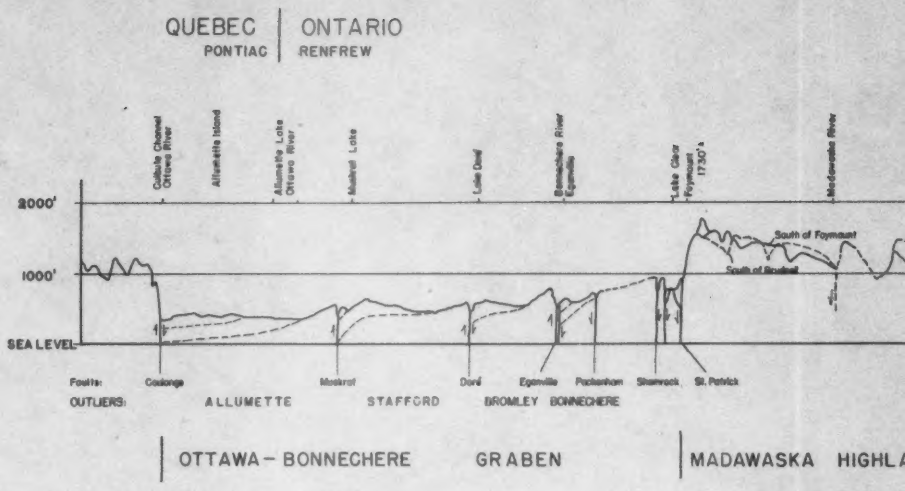
The writer did not study these unconsolidated sediments systematically and was conscious of their presence and distribution principally because of their obscuring the bedrock.

In southeastern Ontario, east of the Moira River, bedrock is sufficiently exposed to permit confident mapping. The glacial geology of the region has been discussed recently by Coleman (1937a).

OTTAWA—BONNECHERE GRABEN

GENERAL DESCRIPTION

The Paleozoic sediments of Renfrew County lie as infaulted outliers within a structurally depressed and topographically low belt, about 35 miles wide, between the Coulonge fault-line scarp on the Quebec side of the Ottawa River and the St. Patrick scarp, south of Calabogie Lake and Lake Clear (Pls. 2A, 6); each scarp has maximum relief of about 1000 feet. Between the Ottawa River and the Bonnechere River, in the northern part of the trough, are three principal south-facing scarps; the Muskrat scarp extends from Muskrat Lake toward the mouth of the Bonnechere, the Doré scarp from Lake Doré north of Renfrew toward Arnprior, and the Eganville scarp and its associates along the north of the Bonnechere from west of Round Lake to northwest of Renfrew, where it approaches the Doré scarp. South of the Bonnechere River, the north-facing Pakenham scarp, trending south of Eganville and Renfrew toward Pakenham, and the south-facing Shamrock scarp,



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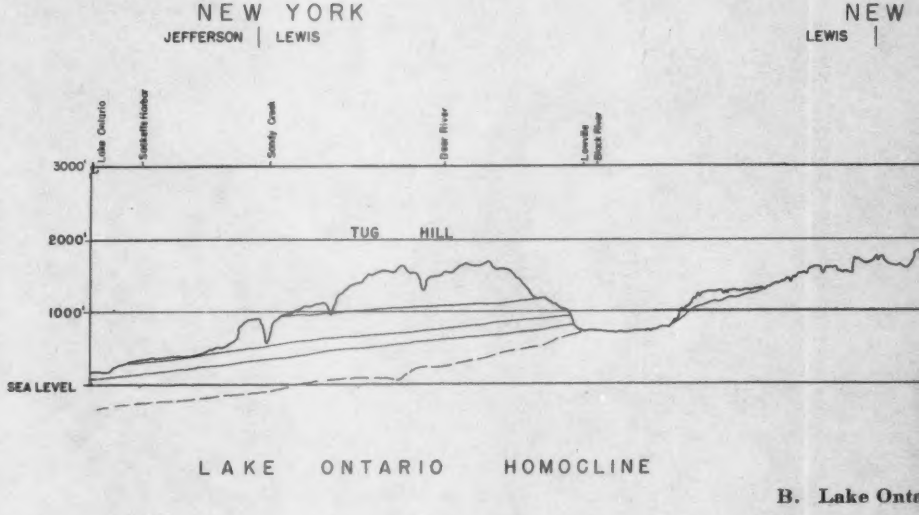

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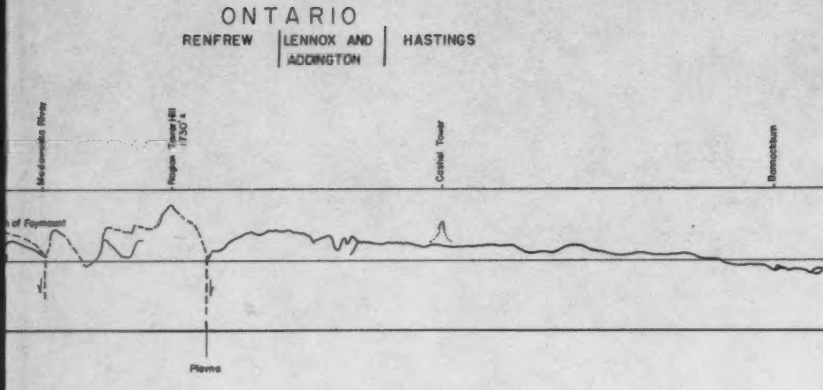
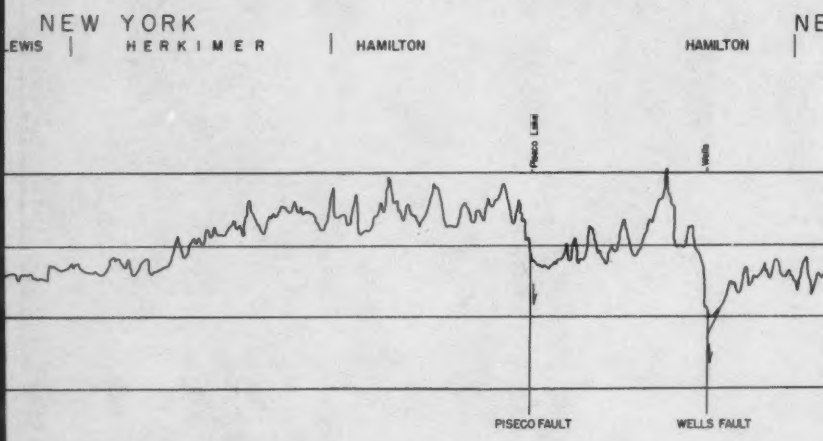


Laurentian Highlands, Quebec, to Lake Ontario



Lake Ontario to the Hudson Valley, New York

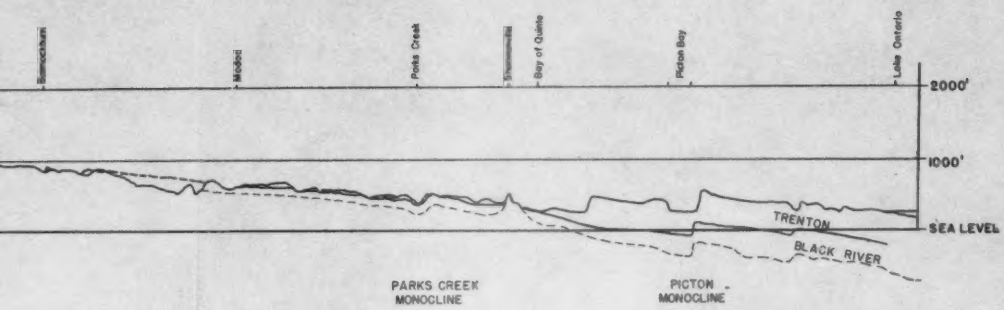
STRUCTURE SECTIONS

0 10 20

Approximate horizontal scale in miles

ONTARIO

HASTINGS | PRINCE EDWARD



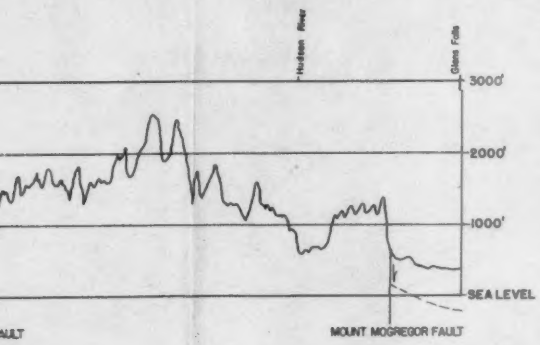
PARKS CREEK MONOCLINE

PICTON MONOCLINE

ANE | LAKE ONTARIO HOMOCLINE

NEW YORK

TON | SARATOGA | WARREN



AULT

MOUNT MOGREGOR FAULT

passing north of Lake Clear and Constant and White lakes, define an upland of crystalline rocks.

The structures of the several Paleozoic outliers along the bases of the respective scarps indicate that they have been downthrown along faults bordering the scarps. The distribution and character of the sediments and the faults will be discussed, beginning with the Coulonge scarp and fault on the north.

Inasmuch as the preserved Paleozoic sediments are at relatively low elevations, they have been considerably mantled by the Pleistocene clays and sands. Exposures are relatively few, and reasonably accurate mapping of the formational boundaries of the outliers is not possible. However, there is sufficient exposure to show quite clearly the approximate structure of the areas (Pl. 6); in a few areas of extensive exposure, detailed maps have been prepared (Pl. 3).

AREAL GEOLOGY

Allumette outlier and Coulonge scarp.—The Allumette outlier, an area of about 200 square miles underlain by Ordovician sediments, includes almost the whole of Allumette Island and the northern peninsula of Westmeath Township, and smaller areas around Pembroke, the northern end of Calumet Island, and the Quebec shore of Coulonge Lake. Exposures are too few to warrant a revision of Ells' (1907) map, which has the limits of the Paleozoic rocks essentially correct but is seriously in error in the formation boundaries. The structure is a shallow syncline, the axis trending eastward from the west end of Allumette Island, approaching the crystalline rocks at Coulonge Lake; the northeast limb is cut out by faulting, and the eastern part of the outlier is principally homoclinal.

Reference has been made to the exposures of the March and basal Rockcliffe formations west of Chapeau; the upper Rockliffe, Pamelia, Lowville, and Chaumont east of Allumette Rapids; the Pamelia along Indian River in Pembroke; the lower Lowville in Pembroke city quarry and Butler's quarry a mile north of Desjardinsville; and the Rockland at Paquette Rapids. Upper Chaumont is exposed east of Cranberry Lake in lot 26, con. VII, Allumette; and Rockland along La Passe-Westmeath Road, at Devonshire Park and Pointe Seche. Ells (1907) mentions a few additional exposures that were not examined.

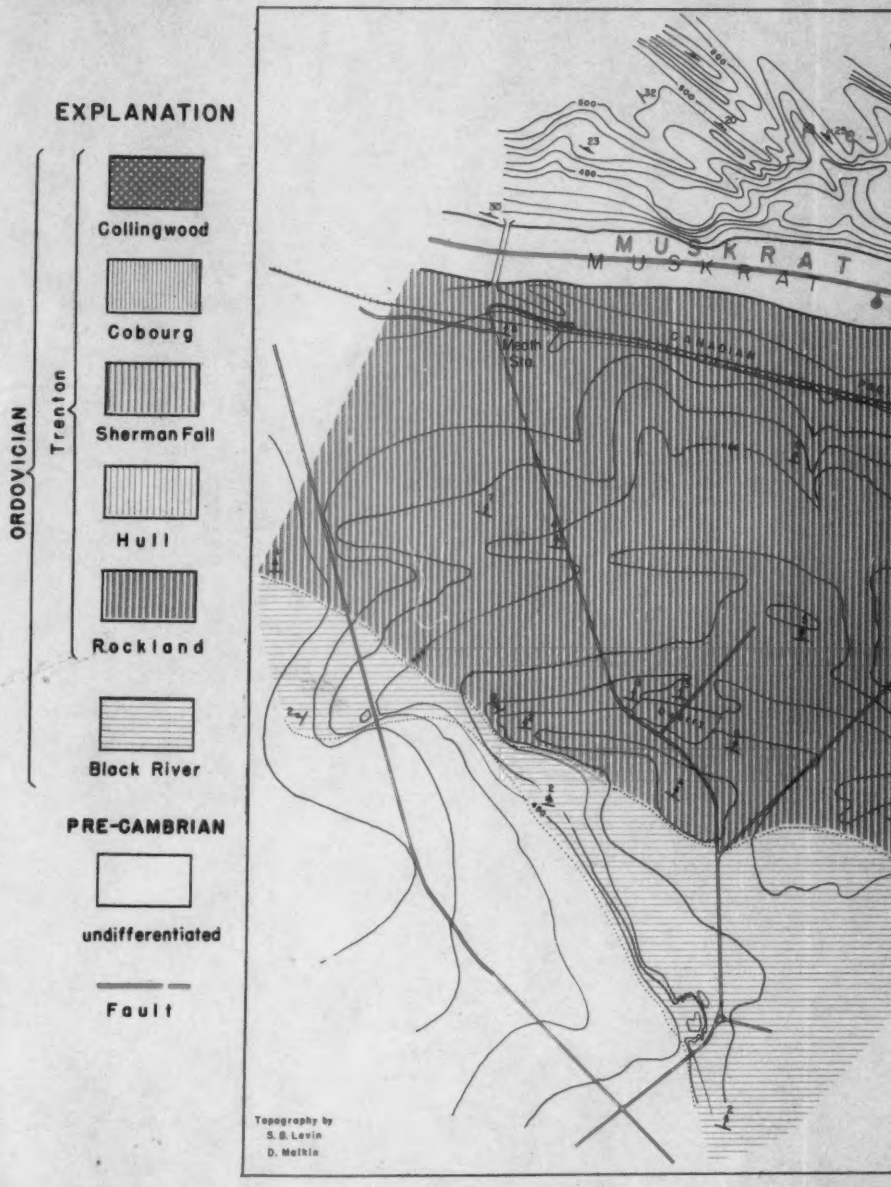
From the elevations of the exposures of lower Lowville at Pembroke city quarry, Butler's quarry, and Allumette Rapids, the dip in the southern part of the outlier is about 25 feet in a mile north of northeast. The dip decreases to about 10 feet in a mile to Paquette Rapids, beyond which exposures of Paleozoic rocks are absent (Pl. 2A). The structural relief within the outlier is about 200 feet. The only direct evidence of faulting is at Devonshire Park, where Chaumont limestone is in contact with gneiss along a subsidiary of the Coulonge fault; in the eastern end of the outlier, the youngest beds are adjacent to the pre-Cambrian scarp, and the general dip is toward it.

North of the outlier, pre-Cambrian rocks rise to elevations exceeding 1300 feet at several points; *see* the Pembroke topographic sheet. The high scarp trends from Waltham to Oiseau Rock, receding from the outlier westward. That the outlier is principally bounded by a subsidiary fault is evidenced by the presence of a 200-foot scarp immediately north of Culbute Channel at Chapeau. The difference in elevation between the highest pre-Cambrian rocks in the scarp and those beneath the Paleozoics in the adjoining outlier exceeds 1000 feet, which would be the minimum displacement of the fault. The Coulonge scarp continues eastward with diminishing relief along the south lines of Thorne and Aldfield townships.

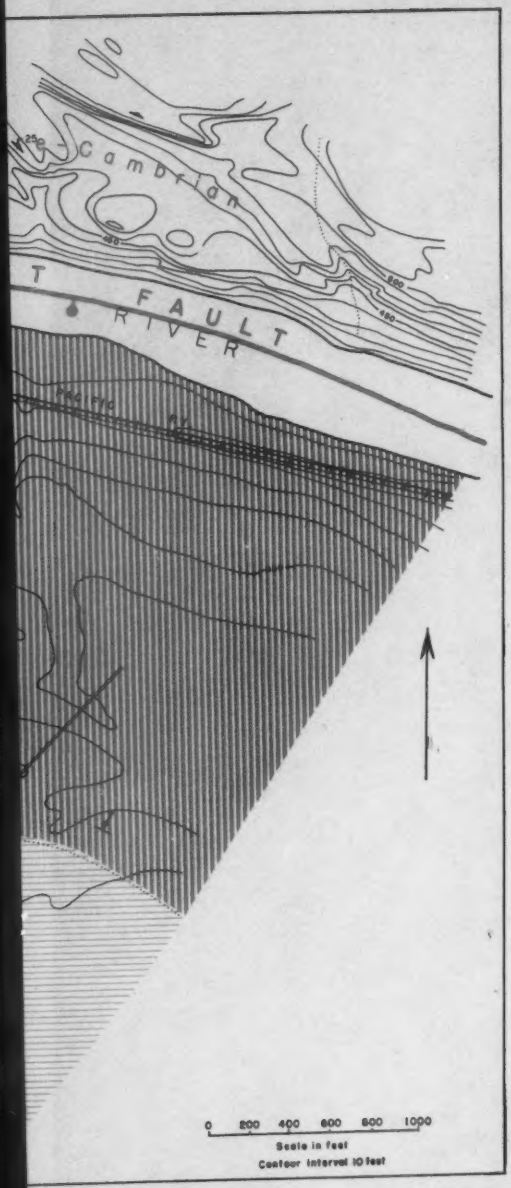
The prominent Eardley escarpment (M. E. Wilson, 1924, p. 7, 57; A. E. Wilson, 1939) is assumed to be formed by a fault of about 1000 feet throw north of Quyon, the scarp continuing westward with decreasing relief into Bristol Township north of Maryland; *see* the Arnprior topographic sheet. En echelon, between the Coulonge scarp north of Allumette Island and the Eardley scarp, is a south-facing scarp from north of Forester Falls across the south end of Calumet Island to the north of Wilson Creek, having a maximum relief of about 400 feet; the pre-Cambrian rocks in this scarp east of Forester Falls are strongly sheared, and Ells (1907, p. 15) records Paleozoic rocks south of the scarp near Portage du Fort. A north-facing scarp about 200 feet high lies north of this, extending from the west of lot 8, con. XIII, Ross, to south of Bryson.

Northwestward from Allumette Island, a fairly continuous escarpment borders the north side of the Ottawa River to Mattawa, where it crosses the Ottawa River and follows the north side of the Mattawa River. Four miles north of Deux Rivieres, the river recedes from the scarp, enclosing an outlier of sandstone and overlying limestone (Barlow, 1899, p. 120); the writer did not revisit the exposures, but there are large blocks of Rockland along the west shore of the river 3 miles above Deux Rivieres (Table 8). A second outlier, 6 miles below Mattawa and east of the river at the base of the scarp, has similar beds (Ami, *in* Barlow, 1899, p. 242). These outliers imply that the Coulonge fault has a displacement of the same order of magnitude as north of the Allumette outlier, probably of about 800 feet.

There is a conspicuous scarp north of the Mattawa River and Talon Lake to north of Nipissing that can be seen from the Lauder and Boulter forestry towers to the south; a view southward from Antoine tower gives the impression that there is a steep, south-facing scarp with a gently dipping back slope, similar to the topography below Mattawa. The escarpment trends along the north shore of Lake Nipissing, receding and decreasing in elevation westward north of Sturgeon Falls, and becoming inconspicuous west of Warren and Vernor. The relief north of Sturgeon



A. Vicinity of Meath station, along M



along Muskrat scarp

B. Vi

GEOLOGIC AND TOPOGRAPHIC MAPS, RENFREW COU

B. Vicinity of Lake Clear, along St. Patrick and Shamrock scarps

Falls is about 100 feet. The presence of Paleozoic sediments on Manitou Island in Lake Nipissing has long been known; the writer re-examined the beds on McDonald Island, where the gneiss is overlain by sandy beds, and these by dolomites having poorly preserved massive heads of questionable *Tetradium fibratum*, suggestive of the Chaumont; Rockland limestones succeed. The dips are irregular as is common elsewhere in beds so near the pre-Cambrian floor. Probably the northern part of Lake Nipissing is underlain by sediments which are bounded by the Coulonge fault or a subsidiary, having a throw of several hundred feet.

Thus, the Coulonge fault can be traced westward nearly 200 miles from Coulonge Lake, the throw diminishing from 1000 feet along the Ottawa to less than 100 feet north of Lake Nipissing. Eastward the throw decreases, and additional en echelon faults separate it from the Muskrat fault to the south.

Stafford outlier and Muskrat scarp.—The Stafford outlier, having an area of about 35 square miles, is southwest of Muskrat Lake and Muskrat River in Stafford Township; the western and southern limits are defined by crystalline knobs west of a line passing near Locksley, Rankin, and Micksburg, and south of Snake River station. The structure is a shallow syncline, with the axis plunging toward the Muskrat fault.

There are no known exposures of beds older than upper Lowville, though arenaceous shale in wells, and float a mile north of Snake River station, are probably from Rockcliffe outcrop. The section of the Chaumont south of Meath station has been described (Table 4). The Chaumont and Rockland are extensively exposed in this area (Pl. 3A), and their contact can again be traced from south of Mud Lake to the line between lots 16 and 17, con. V, Stafford, where it passes beneath drift into Alice Township. The Chaumont is also well exposed in the middle of lot 3, con. I, Stafford.

The Muskrat scarp is fairly regular in trend except at Meath station, where it is offset about half a mile westward on the north; there is a corresponding change in trend of the Chaumont-Rockland contact (Pl. 6). The sediments in the outlier dip gently toward the scarp with dips increasing to 10° in the Rockland limestone within 50 feet of the crystalline rocks at Meath. The regional dip can be determined along a line of section from Micksburg to Meath. The elevations on the pre-Cambrian decrease about 40 feet to the mile northeastward toward Micksburg. In lot 3, con. I, the top of the Chaumont has an elevation of 550 feet, and 2 miles northeastward, in Meath Hill, it has dropped to 490 feet, giving a dip of about 30 feet to the mile. The thickness of the pre-Rockland between Micksburg and lot 3, con. I, should be about 200 feet, of which

the upper 40 feet is Chaumont; the underlying Lowville is probably 50 feet thick, leaving a little more than 100 feet for Pamelia and Rockcliffe, assuming that the March is absent.

The Muskrat scarp is along a fault line because the sediments dip consistently toward it, the youngest exposed beds, at Meath station, having the steepest recorded dip and lying within 50 feet of the scarp. The outcrop patterns of the formations are crescentic, truncated on the northeast by the scarp; the flow layers in the gneiss of the scarp are also cut by the scarp trend (Pl. 3A). Although no fault is exposed, the quarry in the gneiss northwest of Meath station has a slickenside-bounded breccia zone containing Ordovician limestone.

Bromley outlier and Doré scarp.—The Ordovician sediments underlie an area of about 55 square miles in Bromley and Wilberforce townships south of the Doré scarp; the scarp follows the Snake River from Lake Doré (Golden Lake topographic sheet) to a mile west of Osceola, thence trends southeastward along the third and fourth concessions of Bromley. Although the map of Ells (1907) shows this area of sediments as connected with that along the Bonnechere, pre-Cambrian rocks are continuous north of the Bonnechere in Bonnechere Range, and the Bromley and Bonnechere outliers are quite separate; moreover, the structure of the Bromley outlier is probably homoclinal rather than synclinal as he mapped it.

The only extensive exposures are in the sixth, seventh, and eighth concessions of Bromley, between Douglas and the Eganville-Cobden road. Chaumont limestone crops out in con. VII, north and south of the ninth lot road; it underlies Rockland limestone in a cuesta west of the sixth concession road a mile to the north, the contact being exposed along the Eganville-Cobden road. A small area of Rockland is exposed in lot 8, con. XI, Wilberforce; 15 feet of limestone with intercalated shale along Lake Doré in lot 14, con. XIV, seems of Lowville age.

Paucity of exposures prevents proper delimitation of the formations. Dips are consistently low and toward the Doré scarp, but there are no known Paleozoic exposures within a mile of the scarp. It is inferred that the structure is homoclinal to the scarp and that the scarp is along a fault line, because of analogy to other outliers where the evidence is more conclusive. In lots 8 and 9, con. IV, Bromley, a hill of gneiss a quarter of a mile west of the scarp rises about 100 feet above the surrounding clay plain. The gneiss shows prominent N. 30° W. joints and is believed to be in a subsidiary block in front of the principal fault.

Eastward from the outlier, the Doré scarp passes north of Eganville Junction and Renfrew, where it rises more than 300 feet above the pre-Cambrian rocks on the adjoining block. It crosses the Bonnechere River and continues north of Goshen and Glasgow, dying out west of Arnprior. West of Lake Doré, the displacement along the principal trend becomes small, and the principal throw is offset along the Coch-

rane fault west of Lake Doré and returns to a northwestward course along the Black Creek scarp, which can be followed with decreasing throw to beyond Kellys Lake.

Bonnechere outlier and Eganville and associated scarps.—The Bonnechere outlier comprises an area of about 20 square miles, extending

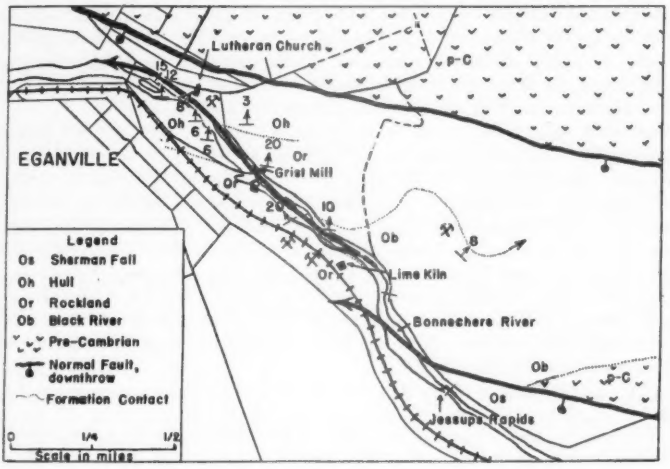


FIGURE 4.—*Map of the vicinity of Eganville, Renfrew County*

about 15 miles in a narrow belt along the Bonnechere River from Mud Lake nearly to Northcote station. Most of the rocks are obscured by drift and alluvium, but there are several exposures that reveal the principal structures. Some were discussed by Murray (1855), who also recognized the presence of faults; Ells (1907) mapped the outlier as synclinal and erroneously connected it with the Bromley outlier. The sediments have generally northward dips toward a system of faults along their northern border. Along most of the southern border, the boundary is the peneplaned pre-Cambrian surface that passes beneath the sediments, but the Pakenham fault seems to limit their outcrop for a few miles south of Eganville. The areal distribution is shown in Plate 6, and the detail of an area about Eganville in Figure 4.

Four areas have considerable exposure: south of the Bonnechere below Douglas, north of the river between Douglas and Fourth Chute, south of the river above the Chute, and along both sides at Eganville and eastward to below Jessups Rapids power dam. At Douglas, east-dipping Pamelia dolomite is displayed in the river, crystalline rocks rising in a 150-foot scarp passing through the village on the north. South of the

river, separated from the Pamelia by a small fault, are northeastward-dipping Chaumont limestones; the higher Chaumont white sublithographic limestone forms a bare, 7-degree bedding slope along Bonnechere Range Road, and these beds are exposed in a small quarry in the hillside to the south (Goudge, 1938, p. 167). A small Rockland outlier lies near the crest of the south-facing cuesta. This homoclinal ridge terminates eastward in lot 35 and has extensive exposures of north-dipping Chaumont and Rockland on its back slope, dips increasing northward from as low as 1° in the cuesta face to 10° near the Bonnechere River. The cuesta faces Moores (Gullton) Creek, and Lowville is interruptedly exposed beneath the Chaumont, best at the east end of the outlier (Table 2). The Pamelia and underlying beds lie beneath the fill of the creek valley, which is bordered by pre-Cambrian on the south; dips suggest that the thickness of the pre-Rockland is about 200 feet. Rockland is exposed along the road between the 47th and 37th lots and extends northward.

West of Douglas, north of the river in cons. IX and X, Bromley, is a terrace of north-dipping Rockland. Small lensing fault blocks adjoin the crystalline scarp on the north. Rockland beds dip 30° toward the fault within 40 feet of the pre-Cambrian, which has slickensided and silicified shear planes dipping 50° southward; the amphibolitic gneiss is severely brecciated and silicified for nearly 100 feet from the scarp face, and prospect pits along the fault have yielded blocks of breccia holding white chert and jasper as well as calcite, with later quartz veins. Aylmer red and green shales with intercalated lensing sandstone are exposed for 8 feet half a mile above Douglas in the river bank; and Murray (1857, p. 96) described a thicker section exposed north of the river. There are poor exposures of Black River beds between the river and the Rockland bench.

At the Fourth Chute is an excellent section of gently warped Chaumont and Rockland. The hill to the north is a Rockland hogback, the beds dipping 10° northward and rising to an elevation of 500 feet, which is 100 feet higher than the river below the chute; a few yards to the north pre-Cambrian gneiss rises above 600 feet in a quarter of a mile. The Rockland dips gently westward at the bridge above the Chute, is rather flat-lying in Sheans quarry a quarter of a mile to the southwest, and with reversal of dip Chaumont rises 50 feet above the river at the Dominion quarry, which has been shown to have some 50 feet of Rockland. The dip becomes westward above the quarry, *Receptaculites*-bearing upper Rockland passing below the road within half a mile with a westward dip of 8°. The Rockland forms a plateau south of the river and is well exposed for 19 feet in a quarry south of the Can. Nat. Ry. a mile west of Dominion quarry (Goudge, 1938, p. 166-167, called Chazy). There are enormous boulders of limestone, mostly Rockland, south of the railroad, suggesting that the formation underlies the area as far southward as the Pakenham fault. Thus in the area southwest of Fourth Chute the beds have been warped, and the axes of some of the structures trend toward the fault.

At Eganville, the crystalline rocks form a scarp rising to 740 feet, nearly 200 feet above the sediments along the Bonnechere. The latter are separated into two blocks by a fault of small throw passing just north of the rapids in the village, and along the river eastward to below the lime kiln (Fig. 4). North of this fault, Rockland limestone and dolomite dipping variably northward is exposed along the river from below the grist mill bridge, where it overlies Chaumont, north to where the north shore road turns northward toward the Lutheran Church. Lower Hull beds are present from the corner to the church (Table 9).

South of the fault, the middle Hull cherty limestone is exposed in the river at Eganville Rapids beneath about 40 feet of higher Hull dolomite dipping 12° north-

ward that forms a hogback south of the river; cherty beds and underlying middle Hull shales reappear along the river north of the road to the mill dam. The lime kiln quarry to the east has excellent exposures of flat-lying Rockland, which becomes steeply north dipping as it approaches the fault but overlies gently dipping Chaumont limestone below the kiln. The fault along the river has a maximum throw of 50 feet in Eganville, decreasing eastward, and is responsible for north-dipping upper Hull south of the river in the village seeming to dip beneath Rockland and lower Hull to the north.

A fault of greater throw must cross the river below the southward bend below the lime kiln, for, although there are anticlinal Chaumont beds at this bend, gently west dipping Sherman Fall beds, stratigraphically 150 feet higher, form the floor and banks of the stream below the dam. There are small exposures of similar beds along the river for a mile to the east, the easternmost, in lot 13, dipping 10° eastward. This fault joins the principal crystalline scarp north of the river to the east, and the scarp at Eganville recedes from the river eastward. A small exposure of 5-degree north-dipping micaceous dolomite lies on micaceous pre-Cambrian granite by the road in lot 12, con. VI, Wilberforce, on the back slope of the more southerly scarp; this block, which bears the sediments exposed at Eganville, evidently rises eastward and is a ramp block (Johnson, 1930).

The Eganville scarp continues westward to near Golden Lake, with a throw of about 400 feet on the adjoining fault; the throw passes to the Cochrane cross fault west of Golden Lake village and turns with a westward trend along the Deacon fault north of the western part of Golden Lake (Pl. 1, fig. 2). The topography is shown on the Golden Lake sheet. This fault has a throw of about 700 feet northwest of the lake, has an associated scarp that continues westward into Algonquin Park north of the Bonnechere Valley, and seems to continue at least to the north of White Partridge Lake. The scarp that rises north of the Bonnechere River below the power dam seems continuous through Douglas, where the throw is about 250 feet; this Douglas scarp passes beneath the Pleistocene sediments at Northcote station; the trend suggests that it joins the Doré fault north of Eganville Junction. Thus the Bonnechere outlier is bounded on the north by a fault system, in which the Eganville fault and Douglas fault are separated by a tilted block that holds the principal sediments in the vicinity of Eganville; the principal displacement is continued westward on the en echelon Deacon fault, which is connected to the Eganville fault by a cross fault along Cochrane Creek.

Pakenham and Shamrock scarps and intervening upland.—The Pakenham fault is evidenced by a north-facing scarp that can be followed easterly from south of Eganville almost to Pakenham, south of Arnprior; *see* the Arnprior and Renfrew topographic sheets. Although it may form the southern margin of the Bonnechere outlier south of Eganville, exposures are not conclusive. Near Pakenham, however,

Paleozoic rocks underlie a considerable area south of Arnprior with a scarp of crystalline rocks rising 300 feet above them on the south, the throw of the fault being about 400 feet;

"the limestones apparently rest upon the crystalline rocks of the Hastings series, from which they are probably separated by a fault extending west from Pakenham along the face of the ridge of crystalline rocks" (Ells, 1901, p. 11).

The southward-facing Shamrock scarp trends parallel to the Pakenham scarp and is 3 to 5 miles south of it. Shamrock village lies on the scarp, and north of Balaclava on Constant Lake the relief is about 140 feet; it passes north of Halladay Creek and White Lake, to the north side of Glen Creek, just south of Pakenham; westward, it passes north of Lake Clear. This scarp is approached by downfaulted sediments in outliers at Ashdod and northwest of Lake Clear; the maximum displacement on the fault is about 200 feet.

The upland between the scarps stands higher than the belts on either side. It is considerably dissected but seems to rise gently southward, so that the surface of the crystalline rocks dips gently northward, presumably reflecting a northward tilt of the horst block. This horst is limited on the east by a southeast-trending fault that follows the west bank of the Mississippi River above Pakenham.

St. Patrick scarp and southern outliers.—The St. Patrick scarp is a continuous high range (Pl. 1, fig. 1) entering Renfrew County in the northwest corner of Burns Township, passing south of Killaloe, Lake Clear, Dacre, and Calabogie Lake, and entering Lanark County along the line between Lavant and Darling townships; it ends rather abruptly south of White, having a length of about 85 miles in Renfrew and Lanark counties. Parts of the scarp are shown on the Renfrew and Golden Lake topographic sheets. It continues westward into Algonquin Park through Clancy Township for an unascertained distance, evidently passing south of Lake La Vieille. The scarp is bordered by Paleozoic outliers south and west of Lake Clear, at Esmonde, and west of Calabogie Lake; and the Barryvale outlier adjoins a diverging scarp that continues eastward south of White Lake. It has been stated that the Shamrock scarp, a few miles to the north, adjoins outliers at Ashdod and northwest of Lake Clear; a subsidiary fault bounds another small outlier forming a peninsula on the north shore of Lake Clear.

Inasmuch as three of the outliers are near Lake Clear, the geology of that area is critical; the writer has been assisted in the study of the area by R. V. Colligan (1940). The presence of Paleozoic sediments was mentioned by Murray (1853) and more specifically by Billings (1858) and Ells (1904). The map by Ells is considerably in

error in respect to both the areal distribution and structure of the sediments; the principal areas of exposure are shown in Plate 3B.

The largest outlier, south and southwest of the lake, is essentially homoclinal, though broadly synclinal with a southward-plunging axis along the stream entering the lake at the southwest corner. The Collingwood shale dips southward along this axis and is 50 feet above the lake at exposures within 50 feet of a nearly vertical face of pre-Cambrian gneiss at the base of the scarp; the shale is strongly jointed and veined and has minor faults. To the east, the Cobourg limestone forms a prominent rising terrace, and along the mountain road half a mile east the Collingwood is 130 feet above the lake, and the beds dip gently southeastward from Sherman Fall exposures near the lake shore; half a mile farther east the Cobourg section of Falls Creek (Table 12) rises more than 150 feet above the lake. The south shore of eastern Lake Clear is composed of gneiss, probably south of the fault along St. Patrick scarp. West of the synclinal axis, the Cobourg terrace rises, the beds dipping 5° eastward in one of the few exposures; beneath them, separated by an unexposed interval, is Rockland limestone in lot 14, dipping 9° N. 80° E., and stratigraphically above granite gneiss along Loon Lake Brook.

A second outlier adjoins the Shamrock scarp northwest of the lake. In lot 16, con. XIII, Grenville marble is near exposures of severely fractured Rockland dipping 25° to 50° southward, dips reversing to 5° northward within 100 yards of the scarp. The sediments probably dip toward the scarp with drag along the bounding fault. The Shamrock fault is thought to pass south of a hill rising 200 feet above the Hurd Creek outlet bay on its east side and to lie somewhat north of the central part of the lake. South of the hill at the outlet, and northeast of the broad western part of the lake, is a steep hill of similar elevation; eastward, it is near a peninsula in lot 23, con. XI, composed of Rockland limestone and dolomite; the latter, near the scarp, dips 14° southward, and the former, near the point of the small peninsula, dips 3° northward. The island of gneiss in the bay to the west of the scarp probably lies north of the same fault.

Thus the three outliers at Lake Clear indicate the presence of at least three faults. The St. Patrick scarp is along a fault having a throw of 1500 feet, for the pre-Cambrian in the axis of the syncline is 200 or 300 feet above sea level, and a mile to the south the scarp rises above 1500 feet and up to 1730 feet at Foymount, farther west. The Shamrock fault seems to have a throw of 200 feet northwest of Lake Clear, and the subsidiary fault to the south has similar displacement. The pre-Cambrian islands in the eastern part of the lake spread eastward. Although the structure across them might be anticlinal their south margin is straight; the lake is deep adjoining them, whereas the crystalline rock surface might be expected to dip gently southward toward Falls Creek if the structure were anticlinal; it is thus probable that a fault, with the south side downthrown, margins the islands on the south. The area west of the lake is sand-covered, and no exposures have been seen except doubtful ones south of Cormac, and westward through Algona and northeastern Brudnell. The absence of pre-Cambrian exposure, together with the presence of pre-Cambrian scarps to the north and south, suggests that the area is underlain by Paleozoic sediments. The scarp that trends eastward from north of Killaloe village to north of Silver Lake resembles other fault-line scarps but is not continuous with those at Lake Clear.

The Esmonde outlier is evidenced by several small exposures along the base of the St. Patrick scarp in cons. VI and VII, Gratton. Along and north of the Opeongo Road for nearly a mile in lots 20 and 31, con. VII, is a northeasterly dipping homocline, with Chaumont dipping 12° N. 60° E. at the west, underlying 50 feet of exten-

sively exposed Rockland. The Hull is sparsely exposed, but Sherman Fall beds in the quarry and adjoining ravine in lot 30 dip 7° N. 55° E. A third of a mile southeast, in lot 29, con. VI, a hogback of upper Chaumont and Rockland, with beds dipping 45° N. 25° E., lies north of the road and is principally drift-covered; the pre-Cambrian is exposed within 100 yards to the south. A quarry a quarter of a mile north of the road near the east line of lot 28 has good exposure of Rockland dipping 15° westward; this stone was used for the Esmonde church. The outlier seems synclinal, with the axis north of the Opeongo Road, but exposures are inadequate. It is believed to occupy much of the area between the St. Patrick and Shamrock scarps and to be somewhat larger than mapped by Ells (1904), who did not indicate the structure.

Two small outliers adjoin Calabogie Lake. In lot 20, con. II, Blithfield, limestone replete with *Tetradium cellulosum* is in fault contact with Grenville marble, and the sediments dip 5° S. 25° E. south of the fault, about a mile north of the St. Patrick scarp; the beds are probably Chaumont, though they may be Lowville. The outlier covers a small area bordered on the north by a fault with a throw of less than 200 feet and extending an unknown distance southward, possibly to the St. Patrick fault, which must have a displacement of more than 1000 feet. East of Calabogie Lake, southwest of Grassy Bay, in lot 15, con. XI, Bagot, light-gray, finely laminated and partially dolomitized limestone in heavy ledges is exposed in a shallow quarry along the bay east of Barryvale; the beds are probably Pamelia, and on the south the exposure continues in a 16-foot terrace which trends eastward into lot 14. The fields are strewn with blocks of sandstone, and it is thought that the Rockcliffe formation underlies Grassy Bay. South of the exposures a scarp of pre-Cambrian trends eastward south of White Lake, and seems to be directed toward the St. Patrick fault south of Calabogie Lake, though the latter fault lies considerably to the south of that adjoining the Barryvale outlier.

Finally, the Ashdod outlier is south of the Shamrock scarp and Halladay Creek in con. IX, Bagot, just west of Ashdod station; it is mapped by Ells as an area of "Potsdam". Pre-Cambrian serpentine and marble are exposed north of the road west of the station; the area to the north is principally drift-covered, strewn with blocks of coarse-textured sandstone and dolomite. Exposures are few and doubtful, but the abundance of large blocks indicates that the sediments are essentially indigenous. It is probable that there is an outlier of north-dipping sediments of the Rockcliffe and Pamelia formations extending from north of the road to the base of the Shamrock scarp, though the limits of the outlier and the formation boundaries are not accurately mappable.

Cross faults.—The Ottawa-Bonnechere graben contains a few cross faults of importance; the most apparent is the Gardez Pieds fault, evidenced by a scarp rising northwest of the depression extending from northwest of Round Lake to Alice. The block north of the Deacon fault-line scarp has a peneplaned surface sloping gently north-northeastward (Pl. 1, fig. 2; Pls. 2A, 5); the elevation decreases from about 1050 feet near the fault, with a monadnock exceeding 1200 feet, to about 700 feet at Kelly Lake, 8 miles to the north. West of Gardez Pieds Creek the surface rises about 200 feet; the highest point on this scarp, Round Lake Tower Hill, 2 miles north of the Deacon fault,

rises to 1200 feet, above an upland elevation of 1100 feet. Joints and shear planes having the trend of the valley are dominant (Fig. 5a); the second principal direction is that of the northwestward-trending Deacon fault.

The upland of the Deacon block terminates southeastward in a scarp west of Cochrane Creek, the upland elevation to the west of about 1000 feet dropping to about 700 feet on the east. This scarp becomes inconsequential east of its junction with the Eganville fault, but the trend is in the direction of the fault joining the Doré and Black Creek faults north of Lake Doré, where there is relief of about 200 feet. Reference has been made to a similar offset in the Muskrat fault between Meath station and Mud Lake.

The effect of the cross faults is to carry westward the displacement of the northwest-trending faults, joining en echelon northwest-trending principal faults. Thus, the displacement on the Muskrat fault along Muskrat Lake is carried westward on a cross fault and continues along Mud Lake; that of the Doré fault is offset on a cross fault to continue on the Black Creek fault to the west; and the throw of the Eganville fault becomes negligible at Cochrane Creek, but there is a corresponding increase in the throw of the Deacon fault 3 miles to the west.

Evidence of faulting.—The presence of faults cutting the Paleozoic rocks was noted by Murray (1855, p. 95), who writes of "a dislocation running N. 62° W." at Douglas, and "a succession of small dislocations" at Eganville Rapids. Ells (1904) mapped faults in the Arnprior region but seems not to have appreciated their significance in the area to the northwest, for at Lake Clear, where fractured Collingwood shale is within 50 feet of a 600-foot pre-Cambrian scarp, he states that the beds "are in a horizontal position without evidence of faulting" (1904, p. 8); and at Devonshire Park, Quebec, where Chaumont limestone dipping 40° NW. is separated by a narrow zone of shear and gouge from granite gneiss (Retty, 1932, p. 89), Ells wrote that "the basal beds are inclined against the crystalline rocks and are somewhat altered" (1907, p. 17). Moreover, on the maps of the graben area, the outliers are shown as infolded synclines within the crystalline rocks. Wilson (1924, p. 58) mapped the base of the St. Patrick scarp as an assumed fault, as well as the Eardley scarp north of the Ottawa River. Barlow (1907, p. 26), in considering the Nipissing district to the north, expressed the belief that

"the occurrence of such outliers at various points throughout these valleys shows that they existed in very early Paleozoic times"; "the existence of Paleozoic outliers occupying portions of these valleys, seems ample proof of their existence as such from very early time."

A. W. G. Wilson (1904, p. 162) suggested that

"the study of the isolated outliers, such as those of the small areas of limestone in the Lake Nipissing region and elsewhere, may show that they are preserved because thrown into their present protected positions by the downthrow of a fault block."

This suggested origin was demonstrated to be correct in explaining the distribution of the Paleozoic rocks at Lake Timiskaming (Williams, 1915, p. 6-8; Hume, 1925, p. 50; Miller, 1913, p. 120). The character of the faults in the Ottawa district has been discussed (Kindle and Burling, 1915; M. E. Wilson, 1920, p. 15-24; 1924, p. 56-59).

There is conclusive evidence that the distribution of the Paleozoic sediments in the Renfrew County area is directly related to faulting and that the beds have been preserved in downthrown blocks. Linear crystalline escarpments rise hundreds of feet above the Paleozoic outliers. The trend of the pre-Cambrian rocks consistently deviates from that of the scarps, which cannot be subsequent along more resistant rocks in the pre-Cambrian suite. The Paleozoic rocks commonly dip toward the scarps, with their youngest representatives adjoining them; this homoclinal pattern has exceptions in the western part of the Allumette outlier and the Esmonde outlier. Approaching the scarps, the dips tend to steepen, precluding the possibility that the sediments are in synclinal basins; belts of outcrop are truncated by the pre-Cambrian outcrop; and drag is rather exceptional. The sediments in the outliers retain consistent primary characters irrespective of their proximity to the scarps; secondary dolomitization is common near the scarps, however. There is striking uniformity in the thin members of formations such as the Chaumont in separated outliers, a condition strongly opposed to an interpretation that they were originally laid in elongate separated basins. There is close similarity to the beds as distant as those in southeastern Ontario, and it is probable that there was no extensive upland separating the areas at the time of deposition.

The only clearly exposed fault planes seen were those along subsidiary faults at Devonshire Park, where the Chaumont lies against granite gneiss, and west of Calabogie Lake, where similar beds lie against Grenville marble. The distribution of the sediments in the Eganville district and at Douglas indicates that there is faulting within the Paleozoic areas. In some instances there is veining and shearing in the beds near the base of the scarps, as in the Rockland northwest of Lake Clear and in the Collingwood to the southwest of the lake. Joints and slickensides are more common in the pre-Cambrian rocks adjoining the outliers than at a distance from a scarp face. This is particularly well shown in the scarp a mile west of Douglas; silicified, slickensided surfaces of the gneiss dip steeply toward near-by exposures of Rockland limestone, and

brecciation and mineralization are extreme in the marginal gneiss; thin sections show that chertification and brecciation of the crystalline rocks have been followed by the introduction of vein quartz. In these exposures, the effects of faulting diminish rapidly within a few yards of the face of the scarp; and in the eroded Deacon scarp northwest of Golden Lake (Pl. 1, fig. 2) the minor structures in the gneiss give no suggestion of their proximity to a principal fault.

Slickensides near faults are so characteristic of the crystalline rocks that their presence along scarps not adjoined by outliers has been taken as supporting an interpretation that such scarps as the Rocher Fendu and Plevna are fault controlled. Movements along the faults approached the vertical along the fault planes, for most of the slickensides are steep, with little prevalence of eastward or westward components. Locally, the varying directions of dip of slickensides represent adjustments between subsidiary blocks and lenses; the variety is well shown in the marble quarry in the Rocher Fendu scarp a mile northeast of Forester Falls station. Slickensided planes dip prevalently toward the downthrown blocks at rather high angles.

Joint patterns.—The dominant trend of the joints is similar to that of the faults (Fig. 5). This might imply that (1) the faults have developed along the trend of earlier joints, or (2) the joints reflect the same stresses that produced the faults. It will be seen (Fig. 5) that westward-trending joints are more prevalent in the faulted areas than in the Cashel peneplane where faulting is thought to be inconsequential. Along the Gardez Pieds fault, trending east-northeast, the joints are not so preponderantly northwestward as in other parts of the region; thus joints may be more abundant in the direction of the faults because of the faulting. It is thought that the fault trends are a result rather than a cause of joint trends, but that joints have greater frequency in proximity to the faults. This is suggested in the tendency of the displacements to be offset linearly in a rhombic pattern (Pl. 5) as though the forces that produced the faulting were directed at an angle to preceding prevalent joint systems, and adjustments took place principally along one joint system, and partially on another. If this is correct, the stresses were tensional in a more north-south direction than the direction normal to that of the principal faults.

The origin of the joints in the pre-Cambrian rocks of the southern Canadian Shield has received little attention. Northeast- and northwest-trending joints are prevalent in the Cashel peneplane and northwestern New York (Cushing, 1910, p. 103-108). In analysis of the joints in an area north of the St. Lawrence River between Montreal and Ottawa

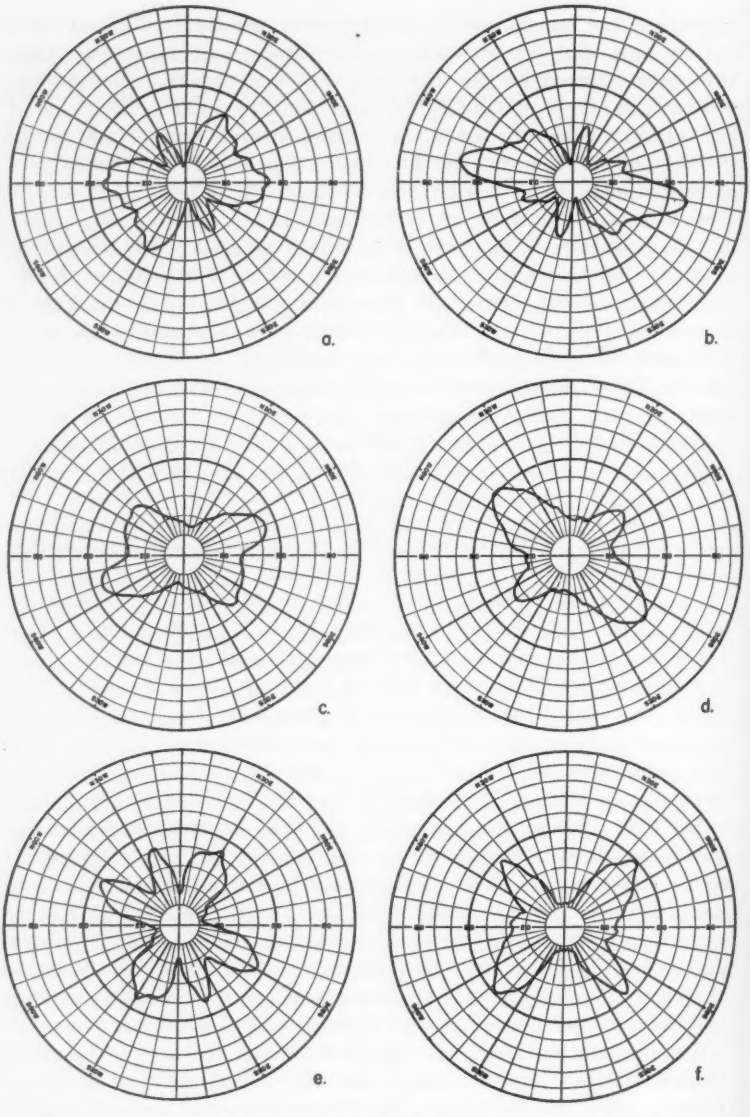


FIGURE 5.—*Orientation of joints and shear planes in pre-Cambrian rocks*

Recorded percentage is that of joints lying within 10 degrees of directional ray

a. Gardez Pieds Creek (70 records);
b. Ottawa—Bonnechere graben east of Gardez Pieds Creek (100 records);
c. Madawaska Highlands in Algonquin Park (63 records);
d. Madawaska Highlands east of Bark Lake (215 records);
e. Cashel peneplane (55 records);
f. Northwestern New York, after Cushing (1910) (127 records).

(Osborne and Lowther, 1936, p. 1360-1362), the prevalent joints in the Grenville metasediments were found to be northwestward and northeastward, parallel and normal to the tectonic axis of the sediments; in a later phacolith intrusive, the trends are N. 22° E. and N. 60° W., similarly related to the tectonic axis. Systematic study of the joints in Ontario may reveal their origin; for the present purpose, it is sufficient that the trends of the joints in pre-Cambrian rocks are probably the result of pre-Paleozoic movements.

Thus the distribution of the sediments in the Ottawa-Bonnechere graben is largely a result of faulting, and the trends of the faults are probably those of earlier joints. The stratigraphic evidence is opposed to an interpretation that the faults are redeveloped pre-Paleozoic faults of small throw, for there seems to be no thinning of the Paleozoic formations as they approach the faults. The evidence favors direct relation of the folding of the sediments with the faulting, for the dip of the beds steepens nearer the faults.

MADAWASKA HIGHLANDS

The Madawaska Highlands, an area 25 miles broad between the St. Patrick and Plevna scarps, is drained by the Madawaska River, which flows eastward along the belt, turning northward across the St. Patrick fault south of Calabogie Lake; the stream descends about 500 feet in the 70 miles from Bark Lake (1000 feet) to Calabogie Lake. Relief is normally about 500 feet, approaching 1000 feet along the St. Patrick scarp; the highest elevations are Foymount and Raglan Mountain, each 1730 feet.[1] Much of the area exceeds 1500 feet, and the highest point in central Ontario, Preston Mountain (1895 feet), south of Opeongo Lake, is to the west in the trend of the highlands.

The rocks are pre-Cambrian crystalline schists, gneisses, and intrusives, the foliation generally trending across the belt (Ells, 1907; Adams and Barlow, 1914; Miller and Knight, 1916). Paleozoic rocks are absent, and the pre-Paleozoic peneplane is so dissected as to make its identification difficult. The St. Patrick scarp on the north is a fault-line scarp. That there is a fault along the base of Plevna scarp is evidenced by a linear topographic break of about 300 feet north of the Cashel peneplane from Ardoch to southwest of Denbigh; this is shown on the Sharbot Lake topographic sheet. Shearing is prominent in the rocks along this scarp, which trends across the structure of the pre-Cambrian rocks; the characters will be discussed in the consideration of the Cashel peneplane.

[1] Elevations have been computed by vertical-angle measurements with telescopic alidade from forestry towers and high elevations to points of recorded elevation and position. Errors are believed to be of the order of 10 to 20 feet.

The interpretation that the intervening highlands are dissected block mountains is based on physiographic evidence gained from traverses across the belt and on views from higher elevations and forestry towers, as well as the prevalence of joints resembling those to the north. The survey was sufficient to warrant confidence that significant faults are present but inadequate to permit more than general mapping. The stream patterns are similar to those to the north in having linear west-northwest trends paralleling the bounding faults; they contrast with the south-flowing streams on the Cashel peneplane, where faulting is thought to be practically absent.

The Madawaska River has a remarkably straight course for 40 miles from Madawaska to southern Lyndoch Township, and high elevations approach within a mile or two of the south. Madawaska tower, 3 miles west of Madawaska, stands on a hill (1700 feet) immediately south of a depression trending from Madawaska to MacCauley Creek. West of Bark Lake (1000 feet) an escarpment rises more than 500 feet in a mile, as along the Cross Lake Road; south of Kaminiskeag Lake (925 feet) elevations exceed 1400 feet; and south of Combermere (900 feet) elevations are more than 1500 feet. The road from the river (880 feet) to Schutt in Raglan rises over 1200 feet in 2 miles. Though Matawatchan Tower Hill (1420 feet) south of Camel Chute is in this trend, there is no evident notch in the hills to the west that would imply the course of a fault. Summarizing, there is a linear depression of MacCauley Creek and the Madawaska River trending east-southeast for 50 miles parallel to the border faults of the highlands, across the regional formational trends, and approached on the south by a scarp rising from 400 to 600 feet above it.

The impression gained from the area to the north of the river is that there is a southward-sloping dissected surface and that the Madawaska River is incised within its southern margin; the view south from Sherwood Tower Hill (1650 feet) suggests these relations. A number of linear divides separate rather long south-flowing tributaries of the Madawaska; decreasing elevation southward on the divides is shown in profiles along the Foymount-Quadville and Brudnell-Quadville roads (Pl. 2A); it should be noted, however, that Quadville Tower Hill (about 1450 feet) lies within 3 miles of the river. It is believed that a dissected southward-sloping peneplane descends from 1500 to 1600 feet by St. Patrick scarp to about 1200 feet at the Madawaska, and that the river has been incised some 300 feet below this surface in a consequent or resequent course along the front of the scarp to the south of it. Presumably the peneplane is pre-Ordovician, for it is analogous to surfaces of this age in the area to the north.

There are other linear depressions within the highlands between the Madawaska River and St. Patrick scarp. One is followed by the Canadian National Railway west of Barry Bay to the Opeongo River and continues westward as Victoria Lake outlet. At Aylen station (1150 feet) hills rise about 300 feet on the north, but there is a higher range close to the depression on the south, which the Opeongo River transgresses in a striking water gap; from Madawaska Tower, this range seems to have a steep north face and gentle south slope, the latter considerably dissected, and with minor ranges controlled by the regional rock foliation. East of Barry Bay, Sherwood Tower Hill (1650 feet) stands 700 feet above a depression passing south of Hopefield that is probably a continuation of that west of Barry Bay; St. Patrick scarp is distinctly to the north, north of Wilno. This depression continues eastward to Brudnell.

Thus, there is a linear depression from the outlet of Victoria Lake to a point east of Hopefield, some 25 miles, with distinct linear ranges or scarps on the south; this may be termed the Hopefield scarp.

A third linear depression is that followed by the Madawaska above Griffith to its sharp northward turn in southern Matawatchan Township, continuing in the valley of Mackie Creek. Farther north is the linear Black Donald Creek valley followed for 2 miles below Black Donald by the Madawaska, and continued eastward in the Mud Lake depression; the range south of Black Donald Creek exceeds 1300 feet, and the upland north of Griffith (850 feet) approaches the river at an elevation of about 1150 feet.

The structure south of the Madawaska is even less conclusively shown. The principal north-flowing streams, the York River and Hydes Creek, are subsequent and follow belts of Grenville marble (Ells, 1907; Adams and Barlow, 1914). Probably the scarp south of the Madawaska represents the fault-line scarp of a southward-tilted block, for there are few tributaries comparable to the longer streams draining from the north. Raglan Tower Hill (1730) is on the crest of a range south of the Madawaska scarp, rising more than 600 feet above the depression to the north. The Plevna scarp can be traced with confidence from Ardoch to southwest of Denbigh at Ashby Lake and has topographic relief of about 300 feet. The course of Papineau Creek south of Burgess Mountain (about 1600 feet) is across the structure, and the upland to the south is at a lower elevation (to 1400 feet). Farther west, Wicklow Tower Hill (1690 feet) stands about 200 feet above the adjoining upland, but there is upland south of Maynooth approaching the higher elevation. If the Plevna scarp transgresses this area, its presence is obscure.

In summary, the presence of linear depressions paralleling bounding fault-line scarps, and cutting across the regional structure, implies that there is control by faulting or jointing. The trend of the prevalent joints in the area is similar to that in the graben to the north (Fig. 5). The contrast in elevation of uplands north and south of the Madawaska River in its longest course strongly suggests that there is a fault-line scarp south of the river, the stream following this fault line.

LAKE ONTARIO HOMOCLINE

GENERAL DESCRIPTION

The Lake Ontario homocline forms the north limb of the Allegheny synclinorium and extends northward to the faulted margin of the Madawaska Highlands and the axis of the Frontenac arch farther east. In southeastern Ontario, the homocline is readily separable into two parts—the Cashel peneplane and the Paleozoic plain. The Cashel peneplane, a resurrected pre-Paleozoic surface, has monadnocks scattered throughout its area, with outliers of the former sedimentary cover along its southern border. The Paleozoic plain is margined on the north by a north-facing cuesta of Black River and basal Trenton limestones; the south-sloping surface is underlain by limestones having a somewhat greater dip, producing other cuestas of which the principal one is that

capped by the Cobourg limestone at the Bay of Quinte. There are scattered resurrected pre-Paleozoic monadnocks, forming structural inliers of the crystalline rocks, and several northeast-trending scarp-bordered monoclines.

CASHEL PENEPLANE

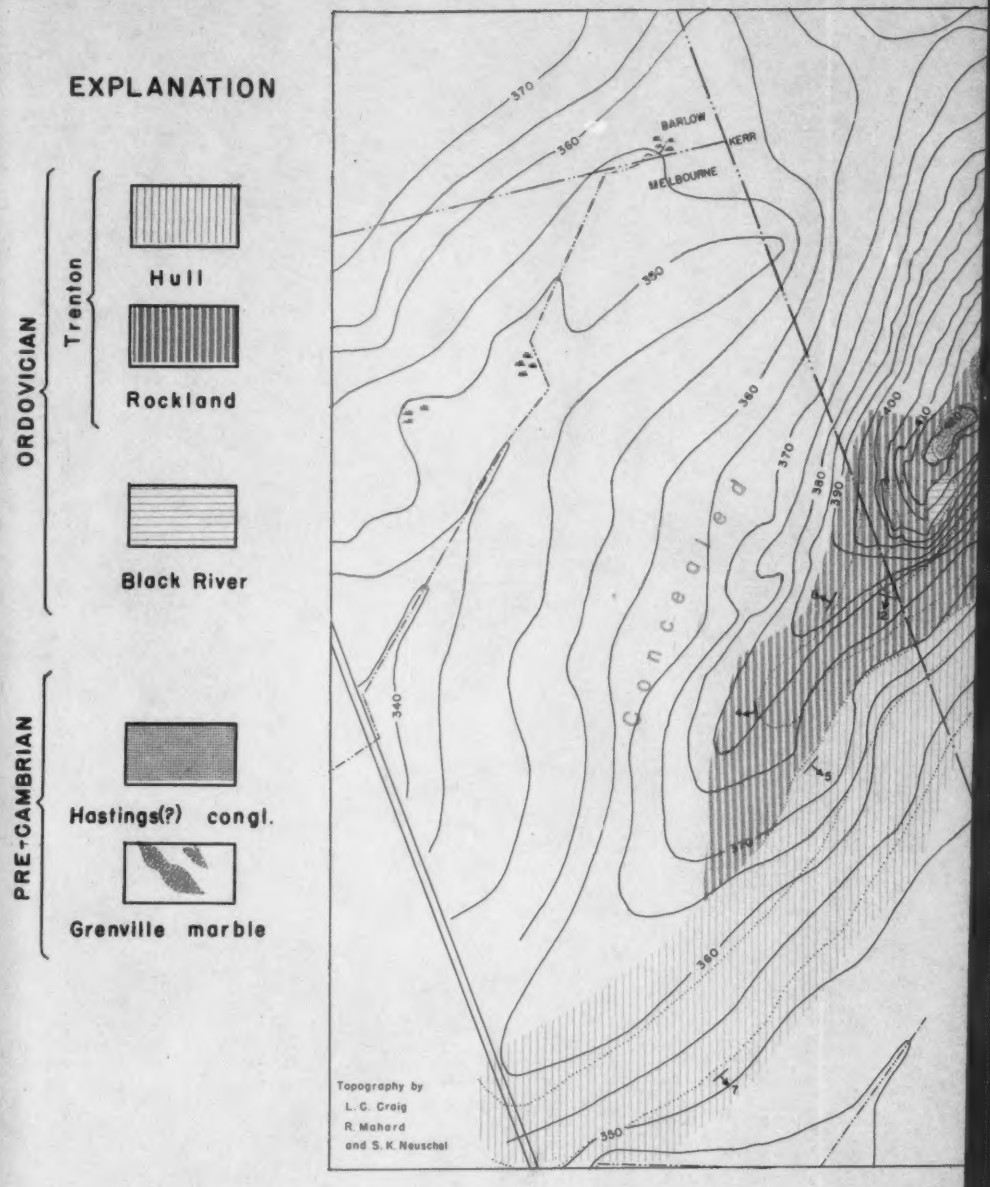
The Cashel peneplane (Cashel Township, Hastings County) is well developed in northern Hastings, and in Lennox and Addington counties, and in northeastern Frontenac County; the underlying rocks are pre-Paleozoic metasediments and igneous rocks. The local relief normally does not exceed 100 feet, though there are several conspicuous monadnocks rising to as much as 400 feet. The peneplane is margined on the northeast by the Plevna scarp, rising about 300 feet; it decreases in elevation southward, passing beneath outliers and a continuous cuesta of Black River and Rockland limestones south of the lakes trending from Beaver Lake, Erinsville, to the Kawartha Lakes in Northumberland County (Pl. 7). Northwestward, the metasediments are intruded by considerable igneous rocks of greater resistance, and the relief becomes greater.

Elevations have been compiled from traverses of upland roads upon the peneplane. The Hastings Road descends from nearly 1200 feet south of L'Amable to 800 feet at the northernmost outlier at Eldorado, and 700 feet at Madoc, at the base of the continuous escarpment; the distance is about 35 miles, and the slope thus about 7 feet to the mile, increasing southward (Pl. 2A). The Addison Road has an elevation of about 1000 feet south of Mazinaw Lake, descending to 600 feet at Erinsville, 25 miles to the south, giving a slope of about 6 feet to the mile.

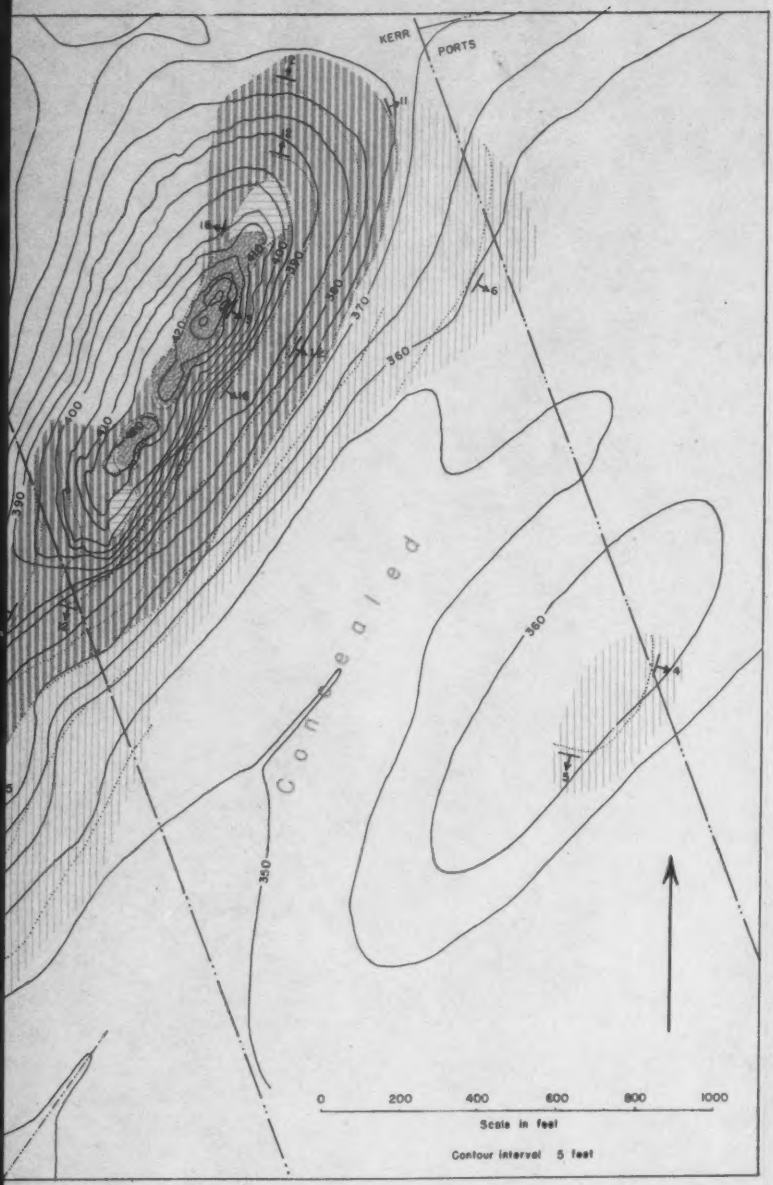
There are several monadnocks, and from their crests the character of the district can be seen. Cashel Tower is on a hill having an elevation of 1535 feet in an area where the peneplane level is about 1200 feet. Grimsthorpe Hill (1225 feet) is in an area having a peneplane level of about 950 feet; Methuen "Blue Mountain" (about 1200 feet) has similar relief, and Tudor Hill (about 1200 feet) rises less; these are composed of intrusive rocks within the metasediments. Barrie Tower Hill (1060 feet) stands 100 feet above the peneplane and is composed of Hastings conglomerate, a formation whose resistance is also responsible for the Bald Mountains, trending eastward north of Kaladar (Miller and Knight, 1914, p. 57.).

The area north and west of the York River is composed principally of igneous rocks. The upland surface is appreciably higher, and Bancroft Tower Hill (1515 feet), the hills to the east (about 1600 feet), a hill 3 miles south of Maynooth (1650 feet), Cardiff Tower Hill (about 1600 feet), and Wicklow Tower Hill (1690 feet) lie in this area. Inasmuch as the Plevna scarp has relief of only 300 to 400 feet and lies along a fault that may decrease in throw westward, it is difficult to locate it in this area.

The contrast between the gently rolling surface of the peneplane and the Madawaska Highlands is best seen from Barrie and Cashel towers. From the former the Plevna scarp stands as a prominent bluff to the northeast, receding and disappearing below the peneplane horizon; southward and westward, the lowlands are interrupted by a few scattered monadnocks. From Cashel Tower, the Plevna scarp is again

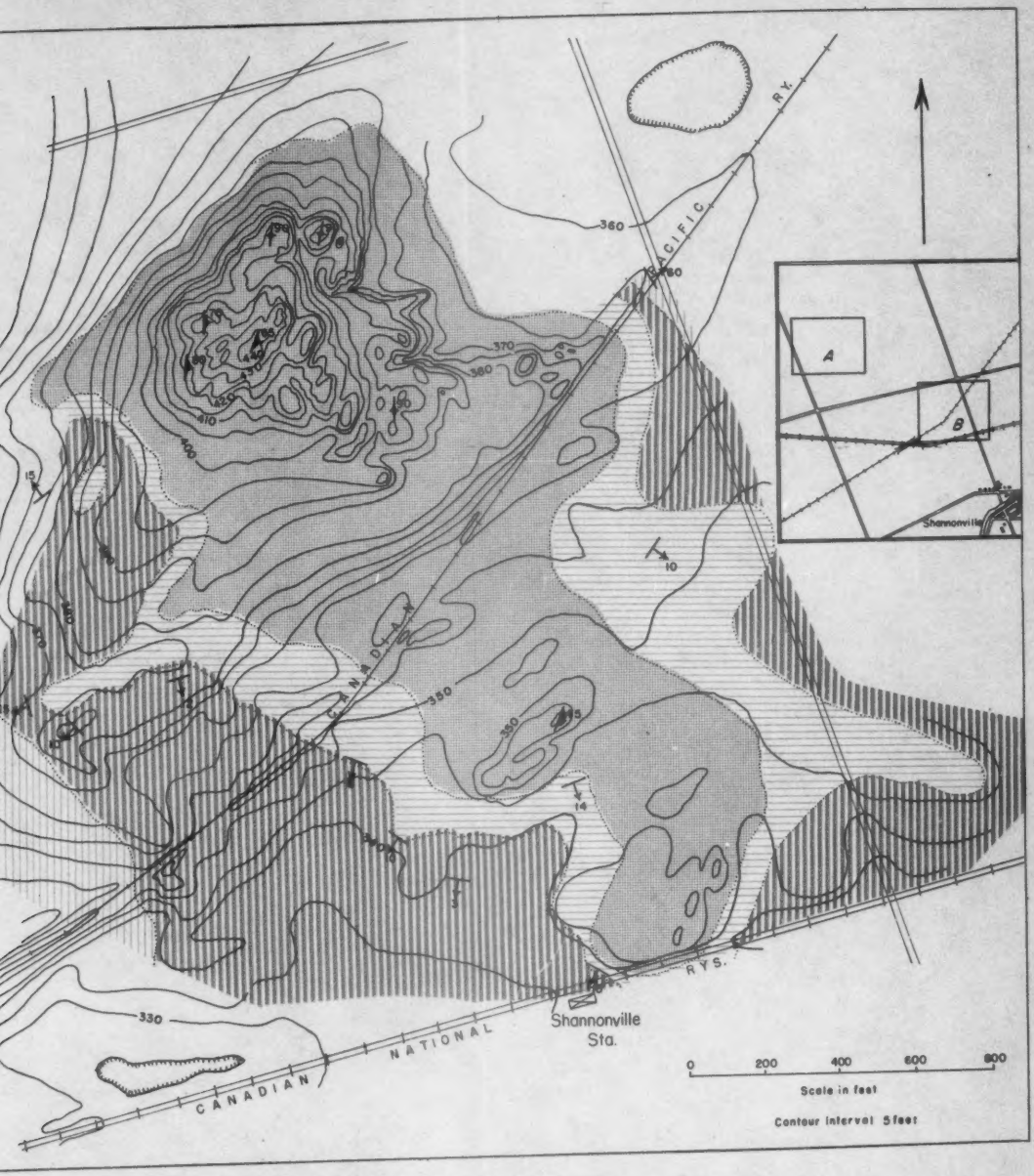


A. West Shannonville



Shannonville pre-Cambrian inlier

GEOLOGIC AND TOPOGRAPHIC MAPS, HASTINGS COUNT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evident in the northwest, with the higher range of Raglan Township rising beyond to 1730 feet; eastward, beyond where the Plevna scarp passes below the horizon, a few monadnocks on its uplifted surface, such as Mattawatchan Tower Hill (1420 feet), are visible. In the northwest, the Dungannon hills rise above the foreground surface quite as conspicuously as the Plevna Scarp in the northeast. The horizon to the south and west has the monadnocks of Grimsthorpe, Tudor, and Methuen; and westward, Cardiff Tower Hill (about 1600 feet) can be seen 30 miles away, a little above the peneplane horizon.

That the peneplane is pre-Ordovician and resurrected is attested by its passing southward underneath the Black River sediments. It is similar to the pre-Ordovician surface northeast of Georgian Bay (Quirke, 1936). That it is older than the Plevna fault is also shown in that the escarpment rises from its surface and has pre-Cambrian metasediments like those of the peneplane, trending almost at right angles to the scarp (Miller and Knight, 1914, p. 72); among the higher hills on the peneplane beyond the scarp is Ompah Tower Hill (1200 feet), composed of Hastings conglomerate in the same belt as the Bald Mountains.

The Cashel peneplane is a resurrected pre-Paleozoic surface having local relief of about 100 feet and developed principally on metasedimentary rocks. Monadnocks and less reduced surfaces on more resistant rocks rise as much as 400 feet and are most numerous in the northwest. The peneplane dips gently southward, the slope averaging about 7 feet to the mile, and steepest at the south. The exposed breadth of the peneplane is about 35 miles, and it continues far to the east and west of the area. It is also represented in the deformed blocks to the north and beneath the Paleozoic sediments to the south.

PALEOZOIC PLAIN

Pre-Paleozoic surface.—The Paleozoic sediments of the homocline are in contact with the pre-Cambrian along a sinuous line at the base of the Black River escarpment at the southern margin of the Cashel peneplane. There are several outliers of Paleozoic limestone to the north on the peneplane, and inliers project through the sediments at scattered localities for many miles to the south (A. W. G. Wilson, 1901; Coleman, 1937b, p. 56). The topographic surface slopes southward more gently than the dip of the structure; thus the pre-Paleozoic peneplane lies at progressively greater depth as the younger belts of sediment crop out. The inliers are the crests of buried monadnocks; thus, the oldest sediments, deposited at the lower elevations on the peneplane, are now exposed farthest north, and the beds adjoining the southern inliers are younger and overlie older strata in surrounding areas. The oldest sediments formed on the margin of an advancing sea and contain terrigenous detritus; they were laid on a rather flat surface and have very

low dips. The younger sediments that surround the inliers were formed when the crests of the monadnocks formed islands; detrital material is sparse and of local derivation; the steep slopes of the monadnocks are reflected in the local, rather steep-dipping attitude of the overlying Paleozoic rocks.

The sandstones and gritty shales—the marginal deposits—are exposed at many localities and vary in character and thickness. They are in contact with the pre-Cambrian on the north side of the Bannockburn outlier, where the Hastings Road crosses the Moira River 2 miles south of Bannockburn; and along the stream crossing the highway 3 miles southeast of Tamworth. Ferruginous basal sandstones outcrop along the road northeast of Beaver Lake, and southeast of the lake, toward Tamworth, the basal limestone contains angular fragments of quartz and gneiss reaching 2 inches in diameter. A classic section illustrating the nature of the basal sediments on a low knob is that near Kingston Mills (Baker, 1916, p. 18-19). There are excellent exposures west of the region along the highway north of Stony Lake, Peterborough County.

The inliers south of the Black River escarpment are of two types. First, there are areas of pre-Cambrian exposed in the valleys of streams. There are a number of these exposed near the margin of the peneplane; the Newburgh inlier and that a mile east of Lonsdale are examples farther south. The top of the pre-Cambrian lies below the surrounding upland, and exposure is due to the superposition of a stream on a low crystalline knob. The area of these pre-Cambrian inliers is small in each case, and the limestones tend to dip rather gently away from the inliers, with little detrital sediment at the base; the contact can be studied with particular success at the Lonsdale inlier, where Black River limestone holding angular pebbles warps over the irregular surface and occupies depressed parts of its surface.

A second type of inliers, which are only partially resurrected monadnocks or "baraboos" on the present surface, are striking topographic features. The structure of the surrounding limestones is similar to that observed in the basal Cambrian in the Ozark region (Dake and Bridge, 1928; 1932). The best exposed and most instructive are half a mile north of Shannonville, 1½ miles northwest of Shannonville, and the Ameliasburg inlier, 5 miles south of Belleville. Farther north, and with little exposure of surrounding sediments, are the augen gneiss inlier a mile west of Naphan and one of dark gneissoid granite a mile to the south. Westward across Central Ontario, the most prominent of this type are Lynch Rock and Galesburg inliers northeast of Lake-

field; Red Rock, west of Bobcaygeon; and Rohalion inlier, 5 miles west of Kirkfield. Each is composed of granitoid rocks.

The inlier a mile northwest of Shannonville Can. Nat. Ry. station (Pl. 4A) is an elliptical hill that rises about 100 feet above the surrounding country and is flanked by steeply dipping limestones; exposed at the crest is a small area of silicated Grenville marble. At the western end, the Rockland limestone forms a plunging anticline, the axis dipping 8° westward and the limbs 15° to each side. On the south side of the hill, the beds dip 20° along the slope, decreasing to 10° in younger beds near the base of the hill. The upper 10 feet of the hill slope has a 6-foot cliff of jointed Grenville with a platform at its base. Rockland limestone fills depressions where joint blocks have been removed, both on the terrace and in the cliff; a specimen of *Columnaria halli* lies in one of the recesses, quite surrounded by the Grenville marble; the limestone contains angular fragments of the pre-Cambrian marble, and similar blocks are inclosed in the basal sediments that warp over the crest of the hill. The inlier is the resurrected crest of a Grenville monadnock that became submerged; the steep slopes of the knob were blanketed by sediments that probably had considerable original dip, increased by compaction of the older limestones of the surrounding plain. The monadnock had local cliffs, probably formed by wave erosion along joints, that have been covered by the advancing marginal sediments. Inasmuch as the Black River group, 200 feet thick in the adjoining area, has been overlapped, the minimum relief of the pre-Ordovician surface can be estimated.

The Shannonville knob (Pl. 4B) north of the village is composed of about 3000 feet of vertical cross-jointed pre-Cambrian conglomerate, with pebbles of phyllite, marble, and granite, the latter attaining a length of 2 feet. The inlier is roughly circular, and the sediments in contact with the Hastings conglomerate are Chaumont and Rockland. They form plunging anticlines off the ends of extending ridges of the pre-Cambrian, the strikes conforming to the detail of the contacts. South of the knob are many low domes of limestone, probably indicating underlying elevations of the pre-Cambrian surface. Similar unbreached domes are numerous in the region and are beautifully displayed in the Chaumont limestone in the vicinity of Read.

Ameliasburg inlier is composed of maroon granite with variable facies; this pre-Cambrian rock extends west of the crest of the hill in two ridges. The Ordovician limestones are Sherman Fall, and specimens of *Prasopora orientalis* Ulrich are abundant; there seem to be some beds of Rockland or Hull beneath them at lower elevation on the south flank of the hill, for *Receptaculites occidentalis* Salter has been collected and has not been seen elsewhere in the Sherman Fall. Near the sinuous contact along the steep south face of the knob beds dip 25° to 45°, and there are many exposures of limestone lying directly on the granite. The beds folding over the west prongs dip 10° to 12° westward. Comparison of the conditions on the inlier with those in Point Anne quarry, 5 miles to the east, attest the amount of overlap (Fig. 6). The quarry has a few feet of Rockland along its north face, overlying 40 feet of Chaumont, and 5 feet of Lowville at the base of the southeast face; drilling in the floor has penetrated an additional 100 feet of limestone without reaching the basement (Goudge, 1938, p. 90); the lower half of this thickness, averaging about 10 per cent dolomite, is probably Pamelia. In the surrounding area 25 feet of Rockland and 85 feet of Hull succeed the Chaumont and underlie the Sherman Fall. Thus the stratigraphic interval between the Pamelia beds at the base of the well and the basal Sherman Fall on the west flank of Ameliasburg inlier is about 250 feet. Inasmuch as the top of the knob is 50 feet higher than the

Sherman Fall exposures and since there is an unknown thickness of Pamelia below the base of the Pointe Anne well, the top of the monadnock must have stood about 350 feet above sea level when the Pamelia sea invaded the area.

The inliers at Shannonville and Ameliasburg indicate that the relief on the pre-Paleozoic surface was as much as 350 feet, that the seas

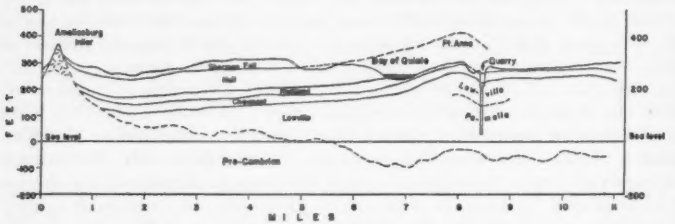


FIGURE 6.—*Section from Ameliasburg inlier to Point Anne, Prince Edward County*

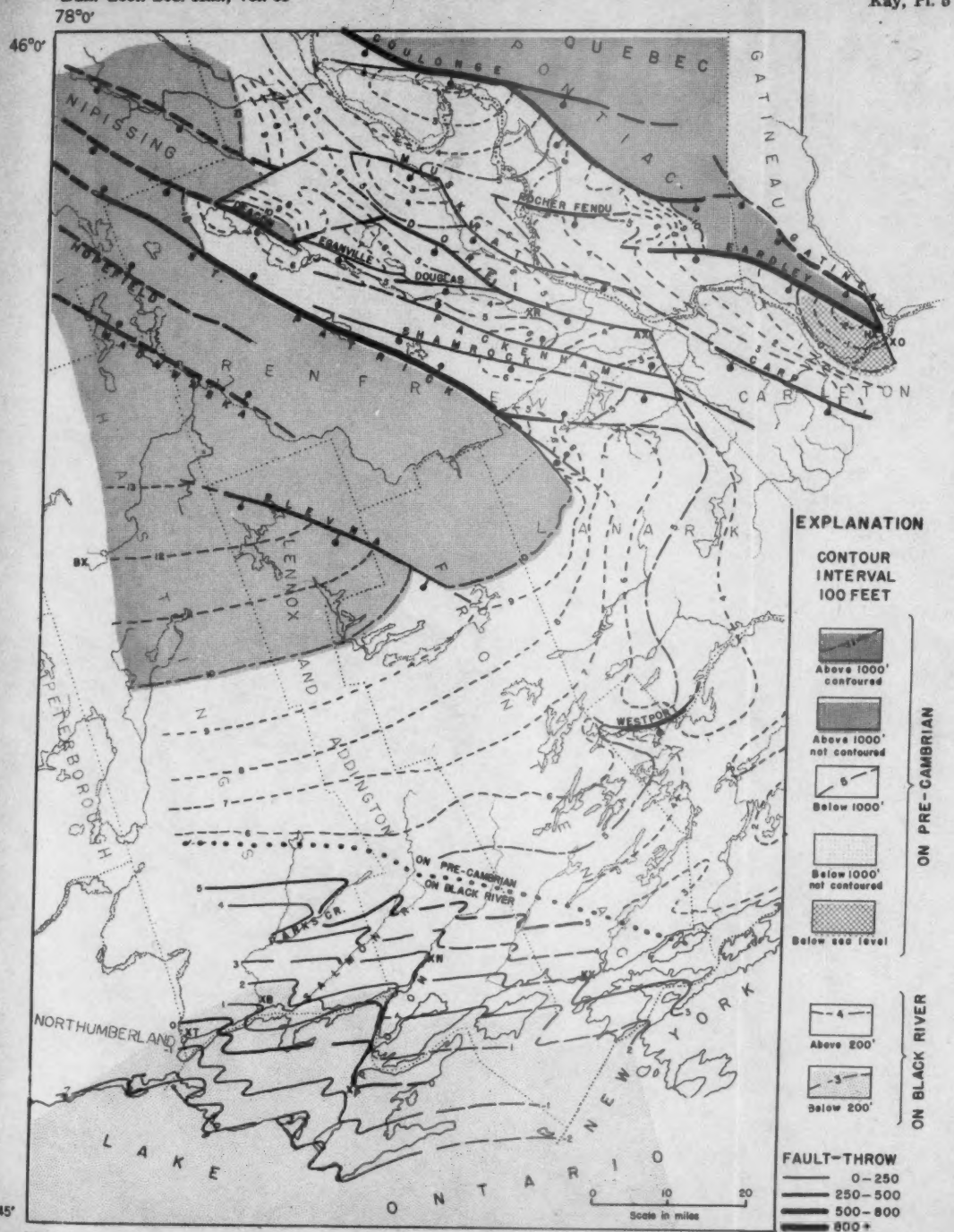
advanced upon these monadnocks, which still stood as islands in later Black River and early Trenton time, and that the structures adjoining the knobs are due mainly to initial dip in sediments deposited on an irregular surface.

Transverse monoclines.—The Ordovician rocks of the Lake Ontario homocline are deformed by a series of northeast-trending monoclines having crests to the southeast (Pl. 5). These structures and the relatively low resistance to erosion of the post-Coburg shales offset the shore of the lake southward toward the east, though the strike in the homocline is consistently eastward. Folds of this trend in Ontario and New York have been recorded, though their nature and significance seem to have been little appreciated.

"There is a series of gentle parallel undulations, which affect the strata, running nearly at right angles across the general strike, the usual bearing being about N. N. E. and S. S. W." (Logan, 1863, p. 184). "Trenton limestone occupies basin-shaped areas upon the Black River to the north of Napanee" (Ells, 1902, p. 179). "The areal mapping [in northwestern New York] brings out the presence of a series of folds that trend to the east of north" (Cushing, 1911, p. 113).

The presence of monoclines is evidenced by their influence on the outcrop of the formations and on the dips of the sediments along them. The best exposures are along the Picton, Salmon River, and Park Creek monoclines. The effects of many of the others on the trend of the Coburg-Collingwood and Chaumont-Rockland contacts are marked.

The Picton monocline (Kay, 1937, p. 278) follows Napanee River, Long Reach, Picton Bay, and the east shore of Spence Lake and Athol Bay (Pl. 7). Northeast



STRUCTURE CONTOUR MAP OF THE REGION

of Napanee Bay, the Chaumont forms the crest of a cuesta of 400 feet elevation east of the town of Napanee; half a mile to the west, Rockland (Napanee) limestone is exposed north of the Can. Nat. Ry. station at an elevation of 300 feet; there is a displacement of more than 100 feet in a line of section paralleling the strikes on each side of the monocline; the sediments are almost horizontal on each side of the structure, but exposures are lacking along its axis. Along the northeast end of Long Reach, west of MacDonald, the Black River-Rockland contact is exposed at water level, dipping 10° N. 65° W.; upper Hull and Sherman Fall beds outcrop across the bay, indicating a structure of about 125 feet. Along Picton Bay, there is a difference in elevation of about 150 feet in the Lower Cobourg (Hallowell) escarpments on the two sides. Southward, sections expose the dipping beds along the axis. Within the town of Picton and southward through the cemetery Lower Cobourg drops 7° westward in a hogback with its crest at 375 feet, 100 feet below the Lower Cobourg cuesta on the east side of the depression; the hill is clearly represented on the northern margin of the Wellington topographic sheet. Half a mile to the south, east of the Cherry Valley Road, Upper Cobourg in a quarry has a 16° N. 40° W. dip, as illustrated by Goudge (1938, p. 158, Pl. 21B); eastward, dips in the Lower Cobourg decrease to 7°, and the beds in the escarpment beyond the swampy depression dip gently southward. Similar dips can be seen southward along the road paralleling and to the east; along the stream a mile east of Woodrous, westward dips in the Lower Cobourg of 2° to 6° give way to decreasing dips in the Upper Cobourg, which is well exposed in a small quarry south of the stream at the Cherry Valley Road. The monocline trends west of Cherry Valley hamlet, and there are consistently west dipping Cobourg limestones along the west shore of Athol Bay to Wicked Point. The topographic expression of this structure is so marked that the Picton and Wellington sheets are useful in instructing students.

There is some reversal of dip along the Salmon River, though the displacement does not exceed a few tens of feet. Westward, the structure is complicated because the Shannonville inliers and domes have dips of initial origin. That the structure on Pointe Anne is not of the latter character is shown by relatively great thickness of Black River, and lack of quaquaversal dips. Rockland limestone on Pointe Anne is in contact with the Chaumont at about 300 feet along the north face of the main quarry; half a mile to the north, shaly Hull limestone is exposed at 260 feet in the old Can. N. Ont. railway cut, and the base of the Rockland must lie below 200 feet. The monocline probably follows the Bay of Quinte west of Belleville, for the base of the Sherman Fall is at the same elevation at Belleville and 3 miles to the south, though there is a southward dip of 20 feet to the mile along the Moira River; and the Hull is anticlinal in the hill south of the Bay of Quinte bridge.

The Park Creek monocline (Kay, 1938) is evidenced in the area adjoining the stream and the Moira River in northern Tyendinaga and Thurlow townships, Hastings County. The regional dip to the north and south of this belt is southward. In Hungerford Township, the top of the Chaumont is at about 650 feet at Larkins, 525 feet at Coulters Hill, and 475 feet at Myrehall, 5 and 8 miles to the south; thus the dip is 20 to 25 feet to the mile. There is little exposure in Huntingdon Township to the west, but the top of the Chaumont drops from 640 feet in the quarry 2 miles south of Madoc to about 600 feet at Crookston (Goudge, 1938, p. 94, the upper 6 feet of limestone being Rockland; Pl. 14), a dip of about 20 feet to the mile. In Western Thurlow Township along the Moira River, the top of the Chaumont is at 370 feet north of Foxboro, about 230 feet west of Canniston—the base of the Sherman

Fall being 350 feet, and 150 feet north of the Bay of Quinte bridge at Belleville, where the Sherman Fall has its base at about 275 feet; the distances being 4 and 7 miles, the dip is about 35 feet to the mile, decreasing to 25 feet. There is continuous exposure of the shaly Hull limestone from Canniston to Belleville, a distance of 2½ miles; the oldest beds at Belleville are but 10 feet higher than the oldest at Canniston, so that the river's gradient is almost the same as the dip of the sediments—about 20 feet to the mile; there are minor warps in this distance, but no appreciable structures.

The Parks Creek monocline is best shown in exposures along the road adjoining lot 5 of Tyendinaga from Chisholms to south of Parks Creek. The Chaumont-Rockland contact is just above the Moira River at Chisholms, at an elevation of about 420 feet. A mile to the south, Hull exposures south of the road corner lie above 465 feet, the base of the Rockland probably being about 425 feet; the lack of a normal southward dip from Chisholms may be due to the presence of pre-Cambrian rather near the surface beneath the Hull, for there is a dome half a mile to the west in lot 3. The top of the Rockland reappears at the road corner, a mile south of Halston at 425 feet, dipping 1° southward; a quarter of a mile to the south, north of Parks Creek, the Rockland forms a syncline, the south limb dipping 2° northward at 340 feet; the Black River in the axis is thus about 300 feet. At the crest of the hill ¾ mile south, beyond Parks Creek, the crest of a westward-plunging anticline of Chaumont is at 445 feet, with a 3° dip on the north limb, and 1° on the south; gentle south dips continue to north of Shannonville inlier. Thus the monocline produces relative uplift of about 150 feet on the south side of Parks Creek; the average dip from Chisholms to Parks Creek is about 50 feet to the mile, but the beds are warped, and the dip is about 20 feet to the mile for 2 miles and then steepens rapidly as the synclinical axis of the monocline is approached. Eastward in Tyendinaga Township, the structure is obscured by drift. The regional dip from Larkins to Myrehall is about 25 feet to the mile; at Myrehall, the top of the Chaumont is at about 475 feet; it is about 500 feet 1½ miles south in lot 16, con. VI, and averages about 500 feet a mile still farther south, west of Read. Thus, there is a reversal of dip across Parks Creek, and though its character is obscured the displacement is not so great as that farther west.

Westward, in Thurlow Township, the Hull is exposed along the Moira River at Latta at 375 feet, the Chaumont-Rockland contact being below 320 feet. Two miles southeast, the contact is above 425 feet in the hill half a mile north of St. Andrews Church and dips southward, so that Rockland is exposed at about 380 feet east of the church. North of Foxboro, in extreme western Thurlow, Chaumont, lying on Lowville, is displayed in quarries on each side of the highway, the top being about 370 feet. Inasmuch as there is a dip of nearly 30 feet to the mile toward this locality from Chisholms to Latta along the Moira River 5 miles to the northeast, and since the elevation at Foxboro is higher than at Latta, the Moira must cross the axis of a syncline below its junction with Parks Creek; inasmuch as there is homoclinical southward dip from Foxboro, the Chaumont to the north must lie on the anticlinal southern margin of the monocline.

The effect of the monoclines on the trend of outcrop belts is strikingly shown by the shore of Lake Ontario, which follows practically the contact of the relatively resistant Cobourg and less resistant Collingwood shale from Port Hope to eastern Prince Edward County. The 250-foot

structure contour on the contact is thus the intersection of the contact and the lake surface.

The linear shore from Cobourg to Brighton is broken at Presque Isle and is offset 12 miles southward to Nicholson Point, the southwest point of Prince Edward County. Upper Cobourg (Hillier) limestone is then exposed quite continuously eastward to Wellington, nearly 10 miles. The regional dip north of Wellington is 20 to 25 feet to the mile southward, and along the Brighton shore; if the normal homoclinal dip prevailed from Brighton to Nicholson Point prior to the formation of the monoclines, the 12-mile offset implies a relative upward movement on the south of nearly 250 feet. The west end of Prince Edward County has not been studied critically, but it is probable from the similarity of the shore line to that farther east that there are several east-northeast-trending monoclines that produce the offset, one being the Salmon River monocline.

Cobourg beds with dips of 10° are exposed on the east side of Yeo Lake Bay at Sandbanks, the shore to the east having gentle south dips; thus Owen Point is essentially an asymetrical southwestward-plunging anticline, the crest of the east limb of a monocline that offsets the outcrop about 5 miles and has a displacement of about 100 feet. Wicked Point and Point Peter have similar structure, the offsets being about 3 miles each, and they represent successive southward uplifts of less than 100 feet; the displacement on the Picton monocline, which follows Wicked Point, thus seems to decrease southward. The rocks along the shore eastward from Point Peter seem to be Lower Cobourg, probably because the Upper Cobourg becomes more shaly and less resistant to erosion than farther west.

The trend of the Cobourg is eastward from Prince Edward County through Duck, Galloup, and Stony islands to Sandy Point, New York (Pl. 7). That this curving trend may be further affected by northeastward-trending monoclines with northward downfolds crossing the eastward-striking beds is shown by the presence of offset gentle slopes south of the islands, with steep-cliffed channels on the northwest between them, as shown on the Duck Island topographic sheet. But there is more definite evidence of the continuing presence of the structures along the North Channel to the Thousand Islands.

The Black River-Trenton contact from the north end of Long Reach of the Bay of Quinte to Chaumont Bay, New York, has a number of southward offsets on the east. The base of the Trenton can be followed from Long Reach, along the south side of Napanee Bay east of the Picton monocline, to the head of Hay Bay and the Can. Nat. Ry. crossing north of Bath. It then swings southward, and the lake shore east of Bath has Black River beds that are at the crest of a southwestward-plunging anticline. Westward through Sandhurst is a long section of gently south-dipping sediments of Rockland, Hull, and basal Sherman Fall, about 150 feet being present in the 6-mile exposure that cuts about 45° across the strike; the beds dip southward about 35 feet to the mile. The displacement of the Bath monocline is probably less than 50 feet, and the structure may follow the course of Millhaven Creek, though this has not been verified.

The strike of the Hull-Sherman Fall contact across Amherst Island from Emerald to the shore south of Stella is east-west, like that of the basal Trenton to the north. On Wolfe Island, however, the Black River-Trenton contact strikes a little north

of east from south of Horseshoe Island to Grimshaw Bay to the west side of Bayfield Bay (Baker, 1916), and then north of Carleton Island, New York (Cushing, 1911). Thus, the lowest Trenton must occupy the north channel from the east end of Amherst Island, then swing south through Lower Gap, and return to an easterly trend through central Wolfe Island. The age and structure of the rocks on the small Snake, Salmon, and Brother islands west of Kingston have not been studied; these would permit more accurate tracing of the Black River-Trenton contact and discovery of the nature of the monoclinal structure.

In New York, the Black River is mapped as exposed along the south shore of Carleton Island, which is composed principally of Trenton; hence the Black River-Trenton contact must swing southwestward through the St. Lawrence and return to the mainland north of Cape Vincent; Carleton Island would thus form the axis of a southwestward-plunging syncline, but its structure has not been examined. The displacement of this St. Lawrence monocline seems to be 100 to 150 feet. Cushing has pointed to the presence of similar structures in the Clayton area that bring the east-west-trending Black River-Trenton contact to the north side of Chaumont Bay.

In summary, a series of northeast-trending monoclines having displacements of from 50 to 200 feet have developed across the southward-dipping homocline on the north and northeast shores of Lake Ontario between Brighton and Chaumont Bay. Each is relatively uplifted on the southeast and has steeper dips on the northwest. Their effect on the distribution of outcrops has produced the principal trends of shore lines and of some of the principal valleys and inlets. The dips in the intervening areas are southward and are about 20 to 30 feet to the mile. The interpretations of age and origin and their bearing on some of the physiographic problems will be considered later.

Regional dips in the homocline.—The regional dip of the surface of the Cashel peneplane and of the areas between the monoclines north of Lake Ontario has been discussed. Drilling south of Lake Ontario as far as the southern end of Cayuga Lake has penetrated the top of the Trenton limestone. Thus, the nature of the structure along a section from L'Amable to Cayuga Lake, a distance of about 180 miles, can now be determined in some detail (Fig. 7; Pl. 2A). There is a progressive increase of the dip southward, except that the monoclines decrease the total displacement.

The Cashel peneplane has an elevation of 1200 feet south of L'Amable; the surface dips southward at about 6 to 8 feet to the mile for 25 miles to Millbridge; from this point the dip increases to about 25 feet to the mile in the following 8 miles to Eldorado (Table 14). The Black River limestone has an elevation of about 850 feet south of Eldorado, and of 640 feet in the quarry south of Moira Lake, giving a dip of 25 feet to the mile in this distance of 8.5 miles. A somewhat

greater dip is attained southward to Latta, where the Chaumont is at an elevation of about 300 feet. From Latta to the shore of Lake Ontario at Marysburgh, 33 miles southward, the dip is affected by the transverse monoclines and, considering only the two localities, averages only 15 feet a mile; however, dips measured across the areas between the monoclines are as much as 20 to 25 feet a mile, and, taking

TABLE 14.—*Regional dip, Lake Ontario homocline*

Locality	Distance in miles from L'Amable	Elevation (feet)			Dip in feet to the mile from previous locality
		Pre-Cambrian	Chaumont	Cobourg	
L'Amable	.....	c. 1200	.....	.....	.....
S. of Millbridge	25	1000	.....	.....	8
S. of Eldorado	33	800	850	.....	25
S. of Madoc	41.5	.....	640	.....	25
Latta	54	.....	300±	.....	27
S. Marysburgh	87	.....	200±	250	15*
S. Lake Ontario	133	.....	2150±	−1650	42
Cayuga Lake	178	.....	5250±	−4700	68

* Measured dip between monoclines, 15-30 feet a mile.

the displacement on the Parks Creek, Salmon River, and Picton monoclines in the line of section, the figure becomes about 30 feet to the mile.

The northernmost well reaching the Cobourg limestone in New York (Hartnagel, 1938) is 46 miles to the south, and the elevation of the Cobourg is about 2000 feet below that north of the lake (Fig. 7), giving an average dip of 42 feet to the mile, which would be increased between any monoclines that may cross the section. The southernmost well in New York is 45 miles farther south, and the Cobourg drops to an elevation of 4700 feet below sea level, giving a dip of 68 feet to the mile. In the last part of the section, there is a suggestion of a transverse monocline that affects both the Ordovician and Silurian about 20 miles south of the lake, with downdrop of about 200 feet on the north.

In a similar section, on a line east-southeast from Sackets Harbor, New York (Pl. 2B), the Hull-Sherman Fall contact, at an elevation of about 300 feet at Sackets Harbor, rises to 1000 feet in 32 miles to Lowville, giving a westward apparent dip of 22 feet in a mile. Eastward, the pre-Cambrian, at about 700 feet at Lowville, rises more than 2000 feet in the 50 miles to the ranges west of Piseco Lake, giving an average dip of about 40 feet a mile; though the nature of the surface is not demonstrated, it is thought that it is the dissected pre-Paleozoic surface. Eastward is a series of west-tilted fault blocks, some of which have small Paleozoic outliers preserved along their western margins; their scarps face principally eastward, and the throw of the Wells fault is about 2000 feet. The section from Lake Ontario to the Hudson Valley at Glens Falls shows that the Adirondack Mountains are block

FIGURE 7.—*Structure section from the Ottawa River to central New York*

mountains, the principal blocks being west-tilted, and suggests that the elevations are remnants approaching the pre-Ordovician surface, which has been considerably dissected. The mountains are not a dome, for the dips are consistently westward rather than quaquaversal; the Adirondacks are more a "semi-dome."

Because the dip of the sediments between Sackets Harbor and Lowville is southwestward, more nearly normal than parallel to the line of section, the true dips are much higher than suggested; the elevation of the top of the Coburg limestone drops from 1200 feet at Lowville to less than minus 300 feet at Camden, and to less than minus 1035 feet north of Constantia, on Oneida Lake, 32 miles and 46 miles to the southwest (Hartnagel, 1938); the regional dip is thus about 50 feet a mile southwestward.

GEOLOGIC HISTORY

GENERAL STATEMENT

If one assumes that at the beginning of Paleozoic deposition the entire region was a plane, the present structural map (Pl. 5) represents the deviation from the horizontal of the pre-Paleozoic surface. The two predominant structural features are the essentially southward-dipping Lake Ontario homocline and the severely block-faulted Ottawa-Bonnechere graben. The beds of the homocline deviate from the form of a tilted plane in that dips in the subsurface increase southward, are reversed along the transverse monoclines, and radiate from and increase around monadnocks on the pre-Paleozoic surface. These deformations of the original "plane" are principally Paleozoic and are a result of the long history of the northern Allegheny synclinorium. In the north, the tilt-block character of the area adjoining the Ottawa is thought to have resulted from deformation about the close of the Mesozoic era or a little later. The subsequent history is one of erosion, and whether long-continued or interrupted depends on the interpretation of the record of denudation.

PALEOZOIC STRUCTURES

Lake Ontario homocline.—The regional dip of the Ordovician rocks in the Lake Ontario homocline developed as sediments were deposited in the northern Allegheny synclinorium. The history can be interpreted only from the record of the entire region, for it is evidenced in the thickness and character of successive formations; this problem of the development of the synclinorium is treated in a separate paper. The deformation was concentrated in times when disturbances southeast of the Allegheny belt formed highlands that produced terrigenous sediments; these were laid in depressed areas of semilenticular form; the homo-

cline lies in the northern sector. The principal deformation was during late Ordovician (Cincinnatian) and still later Devonian (post-Ulsterian). The carbonates, laid in quieter conditions, were influenced in distribution by relatively minor southward tilting. Some, particularly the Pamelia limestone, are thickest in a trough trending northeastward through eastern Lake Ontario. In the Silurian and early Devonian, a cross fold formed in the region of the present Frontenac axis. It is probable that the southward regional dip continued in decreasing amount to the central Ontario highlands, which lie at the intersection of the Cincinnati and Frontenac axes. The principal southward dip is a composite of relatively greater tilting, as thick terrigenous sediments were laid and converged northward, and minor tilting in times when carbonates were deposited.

The lowest sediments in the area have local dips that are much greater and of variable direction. These are initial dips on the floor of seas that deepened away from pre-Paleozoic monadnocks. Additional tilting was produced by compaction, the thicker sections some distance from the pre-Paleozoic crystalline elevations being compacted more than those nearer and thinner. Whereas the regional dip is very low, the initial dips are locally in tens of degrees.

Transverse monoclines.—The age of the prominent northeast-trending monoclines has not been determined. Though they may reflect faults in the subsurface, these have not been recognized in the pre-Cambrian areas beyond the Paleozoic plain; the sedimentary beds form ideal planes with which to measure the deformation, but there is no comparable datum in the crystalline areas that would establish the relatively small displacements. The movements were post-Mohawkian and pre-Pleistocene. An earlier statement (Kay, 1938, p. 1935) that they are at least post-Devonian was based on their direction toward a reported fault in the Devonian in western New York (Chadwick, 1920, p. 117), but this structure has not been recognized in subsequent study (Hamilton, 1937, p. 1586).

TERTIARY STRUCTURES

The region from central Ontario northeastward is characterized by normal faults that have produced block-mountain structures. Evidence as to age in the immediate area is limited; the faults cut late Mohawkian and are overlain by Pleistocene deposits. Evidence from other regions is not conclusive but is suggestive of an early Tertiary age. The limiting relations are those in the Lake Timiskaming, James Bay, and Monteregian Hills areas.

At Lake Timiskaming, immediately north of the area, the principal fault cuts the Silurian Lockport dolomite (Hume, 1925). Along the Moose River, south of James Bay, shales of early Upper Devonian age are disconformably overlain by Lower Cretaceous lignitic shales (Dyer, 1934). The rocks have been deformed and are bordered on the south by an escarpment of pre-Cambrian rocks that is interpreted as a fault-line scarp; the trend is similar to that of the faults in the Ottawa Valley and along the Saguenay graben. The Monteregian Hills are beyond the extension of the Ottawa fault system. The intrusives have been called "post-Devonian" because there are included blocks of Lower Devonian limestone in the volcanic breccia at St. Helens Island, Montreal (Williams, 1910). The absence of pleochroic haloes about radioactive minerals in the intrusives suggested their Tertiary age (Osborne, 1934, p. 30), and glassy dikes have been reported from Mt. Johnson (Osborne and Wilson, 1934). The helium ratio of tinguaite from Mount Royal implies an early Tertiary age (Urry, 1936, p. 122), even though the age in years may need revision (Evans, *et al.*, 1939). It has been suggested that post-faulting mineralization near Arnprior may be related to the Monteregian intrusive epoch (M. E. Wilson, 1924, p. 106).

If the principal normal faults in eastern Ontario and western Quebec are synchronous, or the Monteregian intrusives are genetically related to the faulting, the deformation may be late Cretaceous or early Tertiary. An earlier judgment that it is late Tertiary (Cooke, 1931) was made on independent evidence that seems no more conclusive.

The geomorphic classification of the present graben form depends on the thickness of Paleozoic sediments at the time of faulting. Inasmuch as the maximum displacement along faults is about 1500 feet, the heights of original fault scarps would not have exceeded this. As each of the present scarps is on pre-Cambrian rocks, no part of the present scarp can be a fault scarp if the thickness of the original sediments was more than 1500 feet. The determination of thickness of sediments in early Tertiary involves an estimate of original thickness and consideration of the depth to which erosion has progressed at the time of faulting.

It is thought that rocks older than the base of the Middle Devonian Erian series were about 1800 feet thick; this figure has been reached from isopachal studies of the Allegheny synclinorium that are to be published separately. All or nearly all the pre-Erian sediments are believed to have been present in the area at the time of faulting. If so, no part of the present exposed scarps is above the bottom of the original graben, all faults are along fault-line scarps, and the surface has graben form, rather than being a true graben (Johnson, 1930, p. 363). The

valleys are tilt-block and rift-block valleys and have resulted from the erosion of the less resistant Paleozoic sediments, the pre-Cambrian rocks preserving topographic relief similar to that in the original graben.

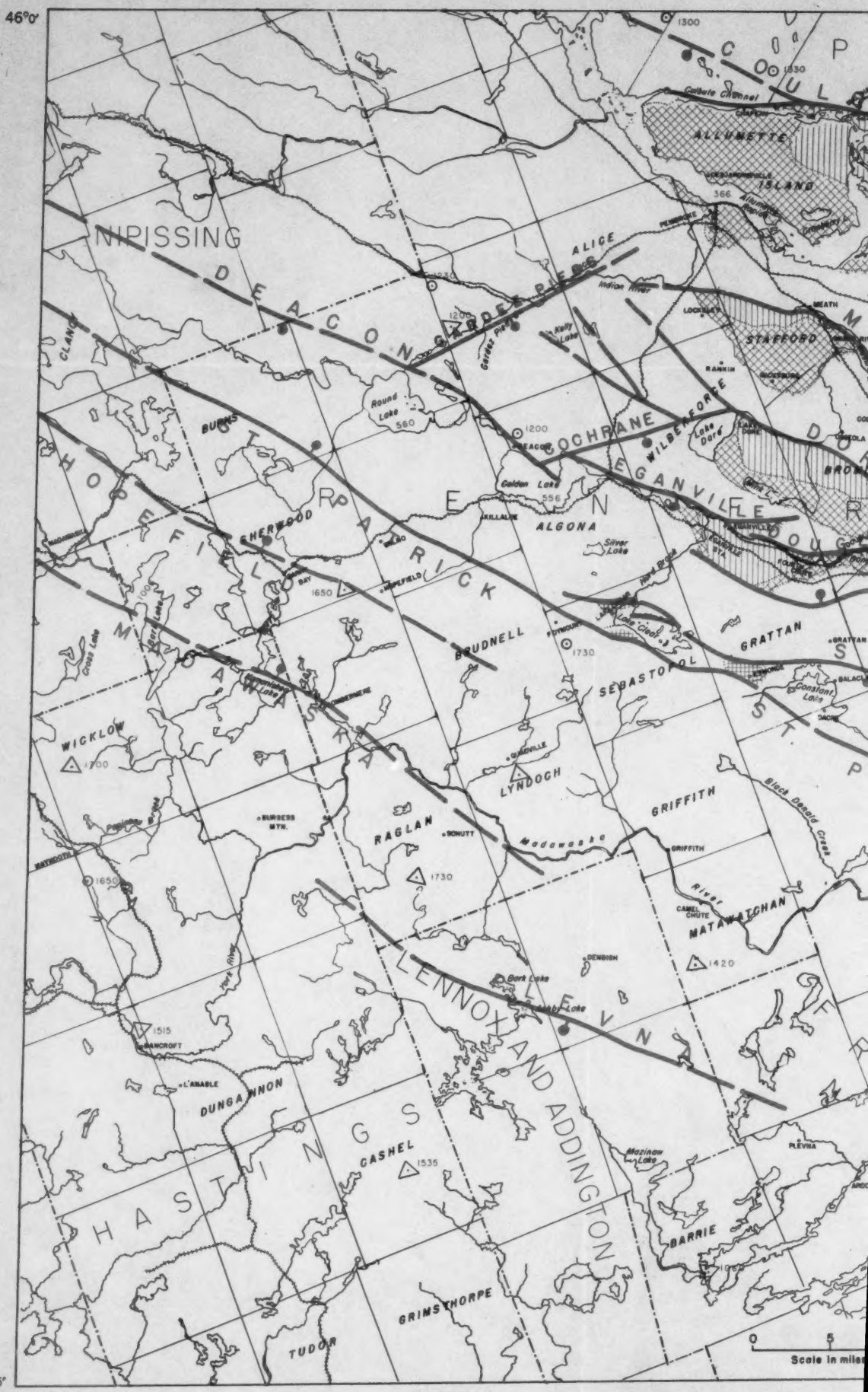
> "It is commonly considered that the long erosion period from the Devonian to the Cretaceous must have resulted in peneplanation of the uplifted Shield; but however great may be the inherent probability of this assumption, direct evidence of its truth is as yet very scanty, and more observations are urgently required before it can be considered proved" (Cooke, 1931, p. 179).

On the contrary, it is the writer's belief that the Shield was considerably mantled by Paleozoic sediments in early Tertiary time (Kindle and Burling, 1915).

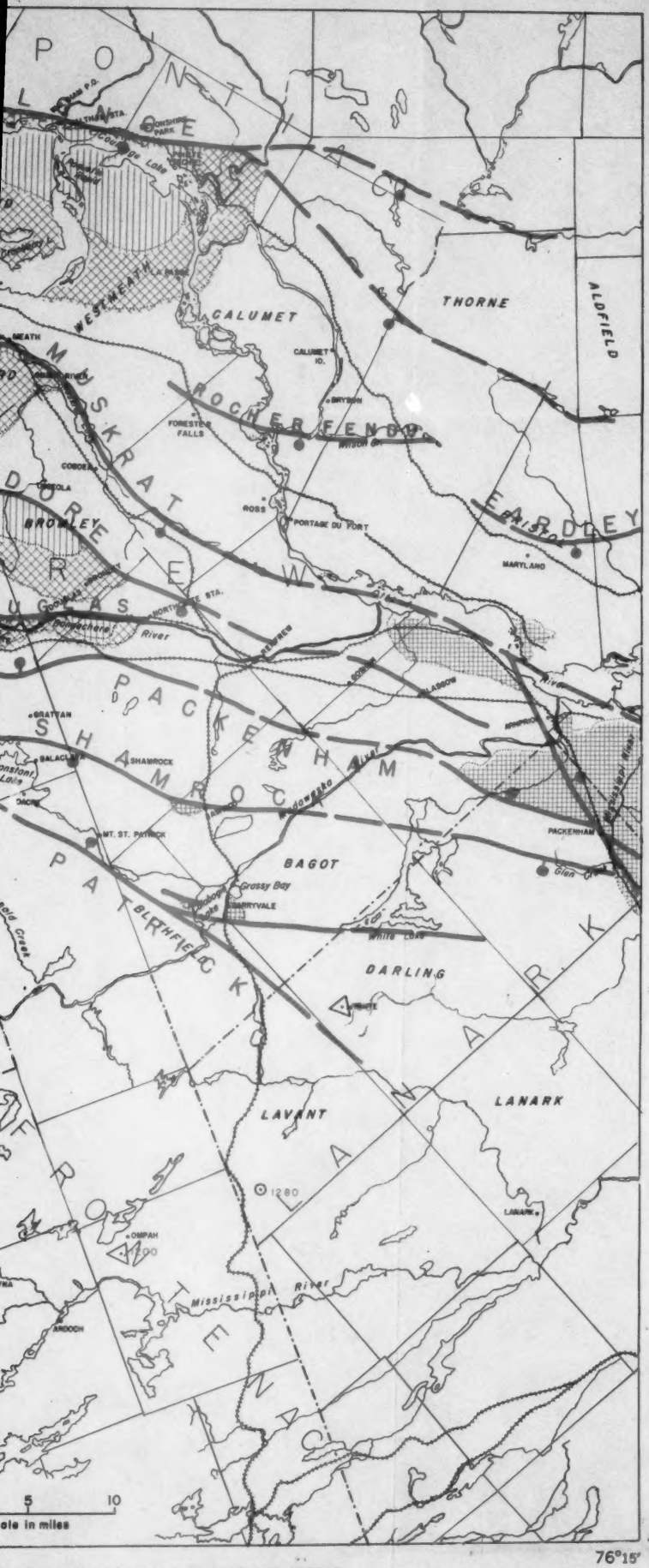
The pre-Paleozoic surface of the Lake Ontario homocline rises uniformly but flattens out northward, and it is probable that the surface of the pre-Cambrian in the upper Ottawa Valley stood about at the elevation of the northern margin of the Cashel peneplane, now about 1400 feet. Thus, the main movement has been downward in the Ottawa-Bonnechere graben (Pl. 2A), but the upthrown sides of fault blocks have been tilted above their original elevation in the Madawaska Highlands. The elevation of the Lockport, which is preserved at Lake Timiskaming, would then have been about 3000 feet. Others have emphasized that the Lower Devonian blocks in the St. Helens breccia at Montreal imply that there were rocks about 3000 feet above the upper Trenton shale at the present sea level; estimates have been 3800, 3300, and 3000 feet (Cooke, 1931, p. 163; Kindle and Burling, 1915, p. 21; Osborne and Grimes-Graeme, 1934, p. 47). The writer can conceive of the thickness being as little as 2500 feet, inasmuch as some of the thicknesses have been based on sections in the Champlain trough to the east, whereas the area lies west of the Adirondack axis. If the St. Helens rocks have been moved down relative to the Laurentian Plateau that rises over 1000 feet on the north, the Devonian would have had a greater elevation prior to the movement.

HISTORY SUBSEQUENT TO FAULTING

Many writers have postulated Tertiary peneplanation of the southern Canadian Shield. In the immediate region, A. W. G. Wilson (1901) considered thoroughly the possibility that the Cashel peneplane is of Tertiary age, rather than a paleopeneplane of pre-Cambrian age; he reached no definite conclusions. The fact that it meets the Plevna scarp implies that it is pre-faulting, for it seems unreasonable that an extensive area of pre-Cambrian should have been removed below the level of the scarp, while rocks of the same character in the scarp remained little dissected. In the area studied, the topography suggests that the crests of the present scarps are essentially at the inter-



GEOLOGIC MAP OF THE OTTAWA-BONNECHERE GRABEN AND



EXPLANATION

PALEOZOIC

ORDOVICIAN

Trenton

Black River and older

undifferentiated

PRE-CAMBRIAN

Fault

△1200 Forestry tower Ground Elevation

AND MADAWASKA HIGHLANDS

section of the pre-Paleozoic surface of the back slope of the blocks and the fault-line scarps of their face. No beveled facets have been recognized, such as should be recorded if there has been peneplanation at a level below the present highest elevations.

On the other hand, the possibility of peneplanation at an elevation higher than the present upland must be considered. Such a hypothesis would require evidence of anomalous drainage courses that would require a second cycle of erosion for their present pattern. Several watergaps suggest such history, but they may have subsequent streams that have captured drainage from higher elevations in tilt-block depressions (Pls. 5, 6). Until more definite evidence of plural history is recognized, the area must be considered as having tilt-block valleys developed in a single cycle in an initial graben, with tilt-block lakes adjoining some of the fault-line scarps. Davis (1925, p. 65-70) described Lake Timiskaming as a "roxen lake," implying that there had been peneplanation since the formation of an initial rift valley, but he presented no evidence of a two-cycle history; Lake Doré has a form strikingly like Roxen Lake, Sweden, but the surrounding upland is not beveled.

The Adirondack Mountains rise sufficiently above the Shield so that they might preserve a record of early Tertiary peneplanation. Their profile (Pl. 2B) shows the prominent influence of block faulting and the effect of the removal of the Paleozoic sediments from the stripped pre-Paleozoic surface so as to form tilt-block valleys (Johnson, 1930, p. 363). Though some have referred to high-level peneplanes, the statements have not been supported by concrete evidence.

CONCLUSIONS

The region in eastern Ontario between Lake Ontario and the Ottawa River is separable into two principal parts. In the northern, normal faults, principally of west-northwest trend, have deformed the pre-Cambrian surface to form the Ottawa-Bonnechere graben and the block mountains of the Madawaska Highlands. Ordovician sediments are preserved only in infaulted outliers. In the southern part, the Lake Ontario homocline comprises the Cashel peneplane and the Paleozoic plain to the south. There are prominent initial dips in basal sediments around monadnocks on the pre-Paleozoic peneplane and transverse monoclines that offset belts of outcrop and direct the courses of streams and lake shore.

The structure of the Lake Ontario homocline is principally of Paleozoic origin. The Cashel peneplane is a stripped pre-Paleozoic surface, for it is broken by a fault-line scarp on the north and passes beneath the Paleozoic plain. The faulting is believed to have been post-Mesozoic.

Inasmuch as the relief in the north is directly dependent on this faulting rather than on retained pre-Ordovician elevation, the distribution of Paleozoic seas must be deduced from the study of the preserved sediments alone.

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Columbia University, New York, N. Y.

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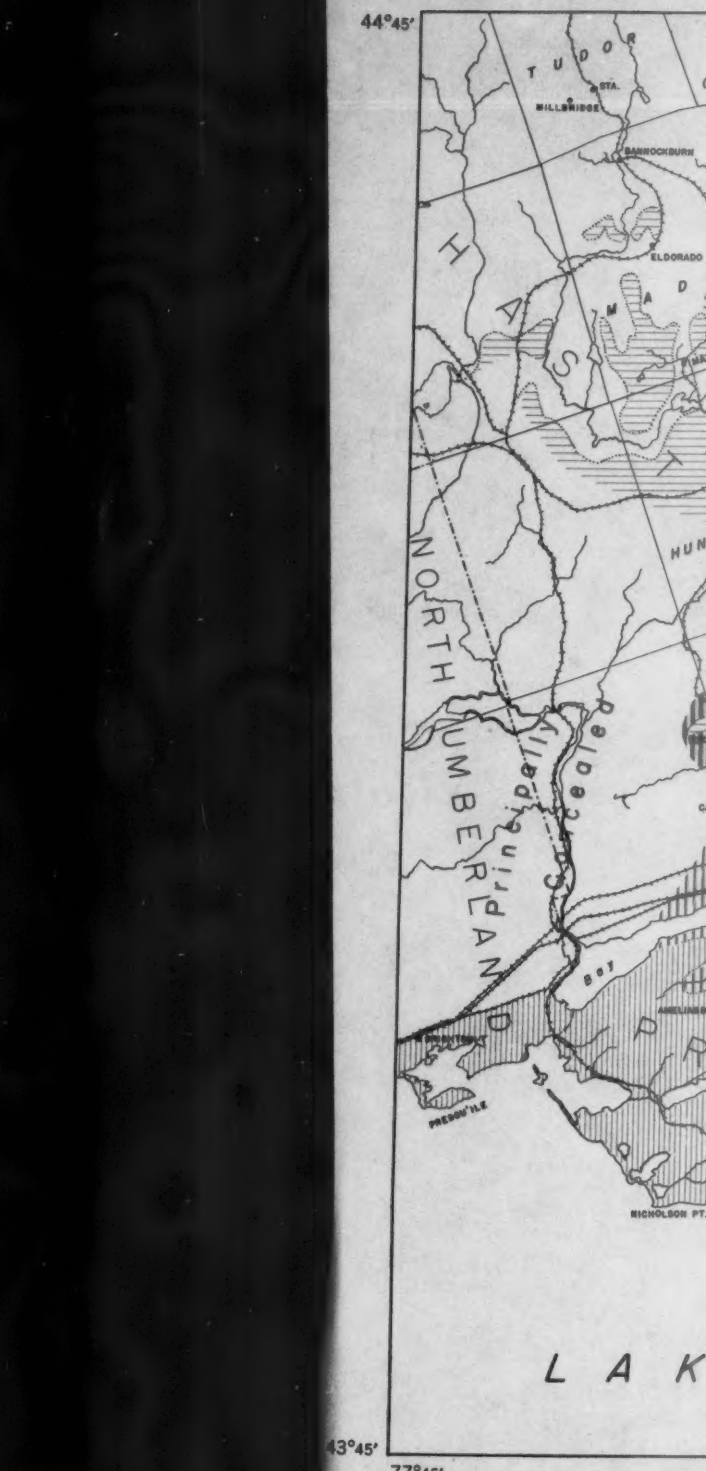
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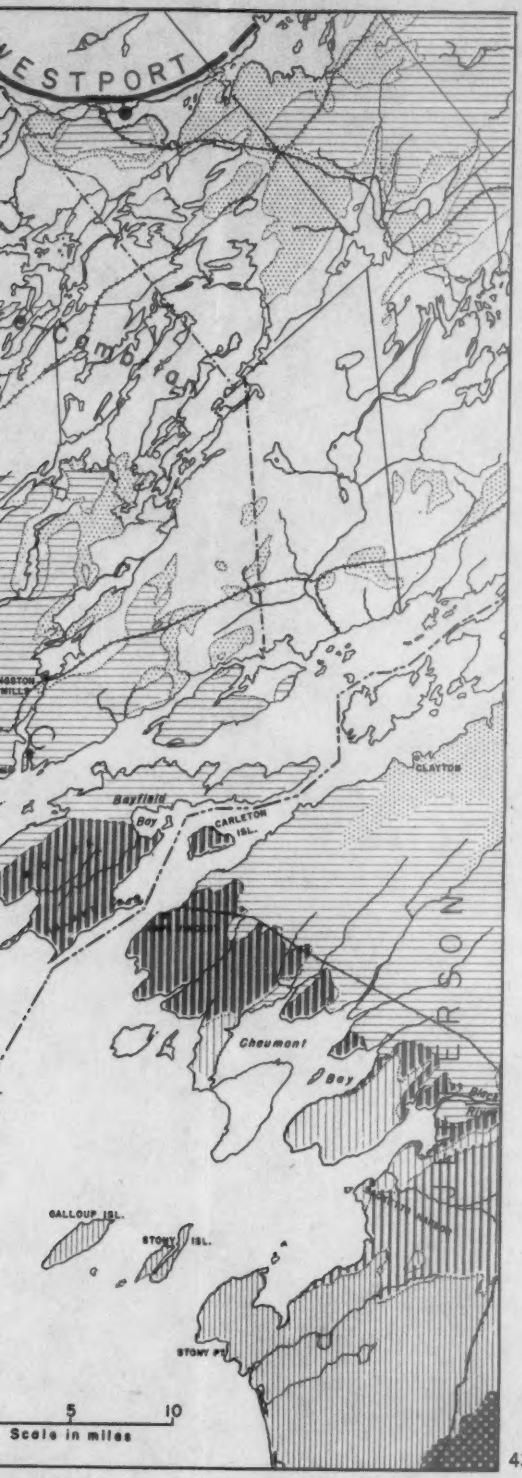
GEOLOGIC MAP OF THE LAKE ONTARIO HOMOCLINE

AP OF THE LAKE ONTARIO HOMOCLINE



EXPLANATION

ORDOVICIAN

Trenton

- Collingwood and younger
- Cobourg
- Sherman Fall
- Hull
- Rockland
- Black River

CAMBRIAN

PRE-CAMBRIAN

- undifferentiated
- Inlier

△1200 Forestry tower Ground Elevation